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THE GYRATORY TESTING MACHINE AS A DESIGN TOOL AND AS AN INSTRUMENT FOR BITUMINOUS MIXTURE EVALUATION

by

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Joint Highway Research Project
Project No. C-36-6BB
File No. 2-4-28

Engineering Experiment Station
Purdue University

In Cooperation With

Indiana State Highway Commission

Prepared for
Annual Meeting Association of Asphalt Paving Technologists
Williamsburg, Virginia
February 25-27, 1974

Purdue University
West Lafayette, Indiana

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INTRODUCTION

One of the main objectives of bituminous paving mixture design is to select a bitumen-aggregate combination such that the mix so obtained will be as durable as possible and yet be stable. To accomplish this objective, one of the critical aspects is to be able to produce in the laboratory a compacted specimen that is truly representative of the mixture as it will be in service on the road. Most of the present design procedures utilize a constant level of compactive effort which is intended to produce densities (at designed asphalt content) comparable to those occurring in the field after a period of traffic densification. This approach may be open to question because a given level of laboratory compaction cannot be considered to produce specimens representative of the density of all mixtures and service conditions after a specified period of time.

It would be logical to compact specimens in the laboratory to a density which is representative of the field compacted density at the time of construction and then to densify these by simulating the effects of traffic. It is desirable to measure stability continuously during this process. By this procedure it should be possible to select the maximum asphalt content that may be used under a variety of service conditions without excessive loss in stability. The gyratory testing machine can be used in this way for bituminous mixture design (2 - 9).

Based on the above reasoning it seemed useful to undertake a laboratory study to design and evaluate bituminous mixtures using the gyratory testing machine. Accordingly, a mixture type commonly used in Indiana was selected and designed for the optimum asphalt content. The designed asphalt content and the selected gradation were subjected to permitted job-mix tolerances. Specimens covering this range of composition were prepared and tested under simulated field compaction and simulated traffic densification conditions.

It was contemplated that the results obtained would help in studying the following factors:

1) Evaluation of the gyratory testing machine design method.

2) Influence of simulated traffic densification on the mixture properties. The purpose was to study the capability of the gyratory testing machine to evaluate bituminous mixes at any specified densification effort. Positive results could lead to an estimation of pavement life.

3) Job mix formula and tolerance limits. The sensitivity of the gyratory testing machine when used to study the job mix formula tolerances was investigated. Favorable results could help in modifying specifications to suit field conditions.

MATERIALS AND MIXTURE PREPARATION

Two types of aggregates, limestone and gravel and a 60- 70 penetration grade asphalt were used in the study. The results of tests on these materials are presented in Tables 1 and 2.

To select the aggregate gradation, a job mix formula based on the specifications of the Indiana State Highway Commission (10) HAC (hot asphaltic concrete) surface mixture type B was chosen. For type B surface mixtures, a typical job mix formula issued by the Indiana State Highway Commission contains the following:

1) Coarse aggregate No. 11 is specified.
2) Fine aggregate No. 14-2 (or No. 17) is specified.
3) Percent of aggregate passing the No. 6 sieve is specified to be 47 ± 3.
4) Limits of the percent passing the No. 200 sieve are specified to be 0 to 3.

Table 3 and Figure 1 present the gradation limits specified for coarse aggregate No. 11, fine aggregates No. 14-2 & No. 17, and surface mixture type B.

To obtain the widest possible gradation band feasible within the type B surface mixture specifications, the gradation ranges for all conceivable blends using upper and lower limits of the coarse and fine aggregate sizes were calculated (11). The widest possible gradation band satisfying surface mixture type B was selected for this investigation since this can be the maximum variation within the job mix formula and the permissible tolerances. Table 4 and Figure 2 present the lower

TABLE 1 - RESULTS OF TESTS ON AGGREGATES

Material		Bulk Specific Gravity	Bulk Specific Gravity (Saturated Surface-Dry Basis)	Apparent Specific Gravity	Percent Absorption
Limestone	Coarse Aggregate (Retained #6 Sieve)	2.52	2.58	2.69	2.47
	Fine Aggregate (Passing #6 Sieve)	2.41	2.49	2.62	3.34
Gravel	Coarse Aggregate (Retained #6 Sieve)	2.61	2.66	2.75	1.85
	Fine Aggregate (Passing #6 Sieve)	2.49	2.53	2.60	1.71

TABLE 2 - RESULTS OF TESTS ON ASPHALT CEMENT

		Test Method
Solubility in Carbon Tetrachloride, %	99.85	ASTM D4
Penetration, 100 grams, 5 sec, 77 F (25 C)	67	ASTM D5
Loss on Heating, 50 grams, 5 hr, 325 F (163 C), %	0.04	ASTM D6
Penetration of Residue, % of Original	84	ASTM D5
Specific Gravity at 77 F (25 C)	1.019	ASTM D70
Flash Point, Cleveland Open Cup, F (C)	400^+ (204^+)	ASTM D92
Ductility at 77 F (25 C), 5 cm/min, cm	100^+	ASTM D113
Kinematic Viscosity at 275 F (135 C), cSt	456	ASTM D2170
Absolute Viscosity at 140 F (60 C), poises	2426	ASTM D2171
Spot Test	Negative	AASHO T 102

TABLE 3 - GRADATIONS AS SPECIFIED BY INDIANA STATE HIGHWAY COMMISSION

U.S. Sieve Size	Total Percent Passing			
	Coarse Agg.	Fine Agg.		Surface Mixture
	Size No. 11	Size No. 14-2	Size No. 17	Type B
(mm)				
1/2 in (12.7)	100			100
3/8 in (9.52)	75-95	100		80-97
No. 4 (4.76)	5-20	98-100	100	40-60
No. 6 (3.36)	--	--	--	35-55
No. 8 (2.38)	0-5	75-95	90-100	30-48
No. 16 (1.19)	--	50-75	55-85	18-35
No. 30 (0.59)	--	20-53	20-55	9-24
No. 50 (0.297)	--	6-25	5-35	3-13
No. 100 (0.149)	--	1-17	1-15	0-8
No. 200 (0.074)	0-2	0-3	0-5	0-3

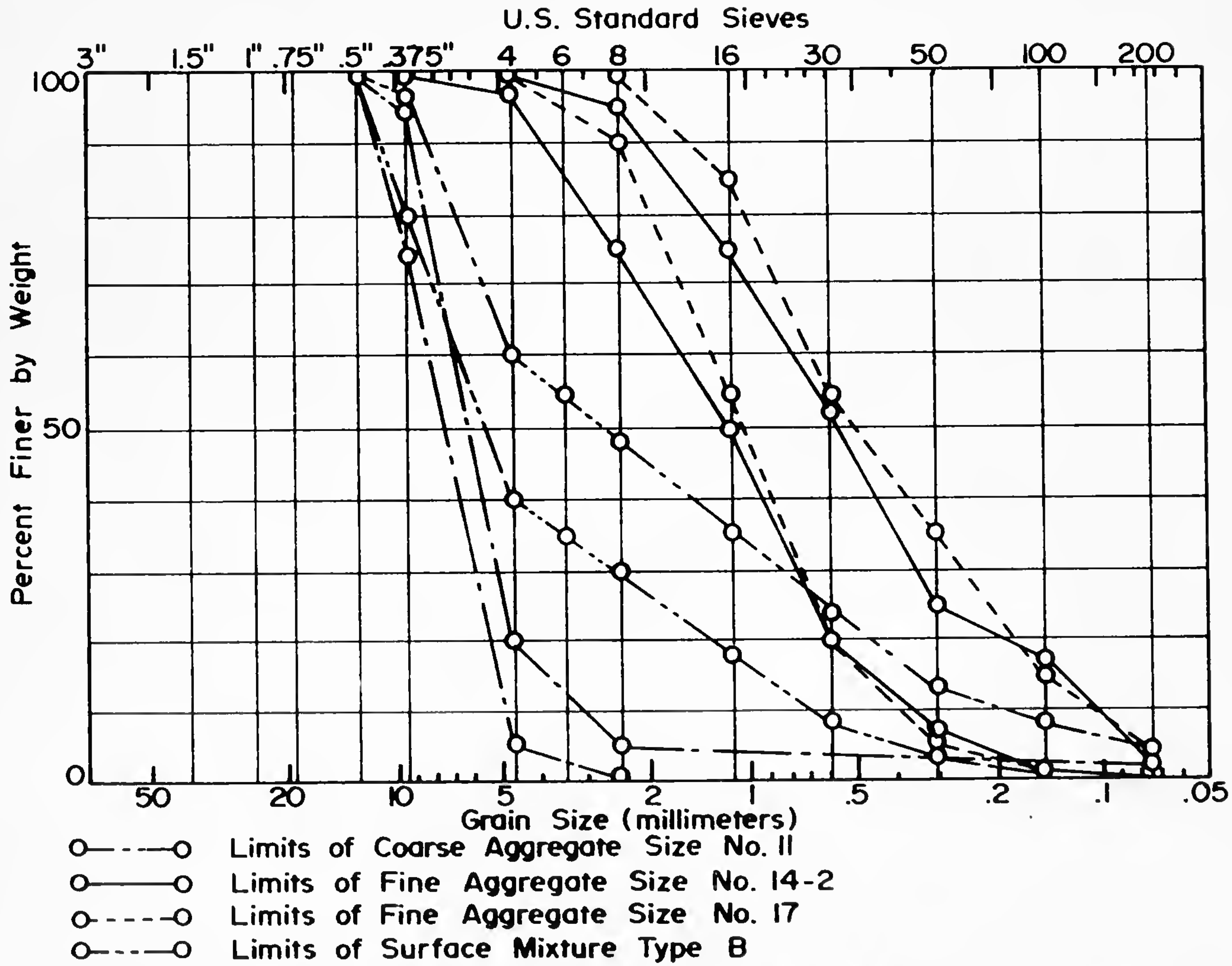


FIGURE 1 - GRADATIONS AS SPECIFIED BY INDIANA STATE HIGHWAY COMMISSION.

TABLE 4 - SELECTED AGGREGATE GRADATIONS

U.S. Sieve Size	Total Percent Passing		
	A Lower Limit*	B Middle Point	C Upper Limit**
(mm)			
1/2 in (12.7)	100	100	100
3/4 in (9.52)	85	91	97
No. 4 (4.76)	45	52	59
No. 6 (3.36)	44	47	50
No. 8 (2.38)	34	41	48
No. 16 (1.19)	23	29	35
No. 30 (0.59)	9	16.5	24
No. 50 (0.297)	3	8	13
No. 100 (0.149)	0	4	8
No. 200 (0.074)	0	1.5	3

* Lower Limit - Refers to Coarser Limit of the Gradation Band

** Upper Limit - Refers to Finer Limit of the Gradation Band

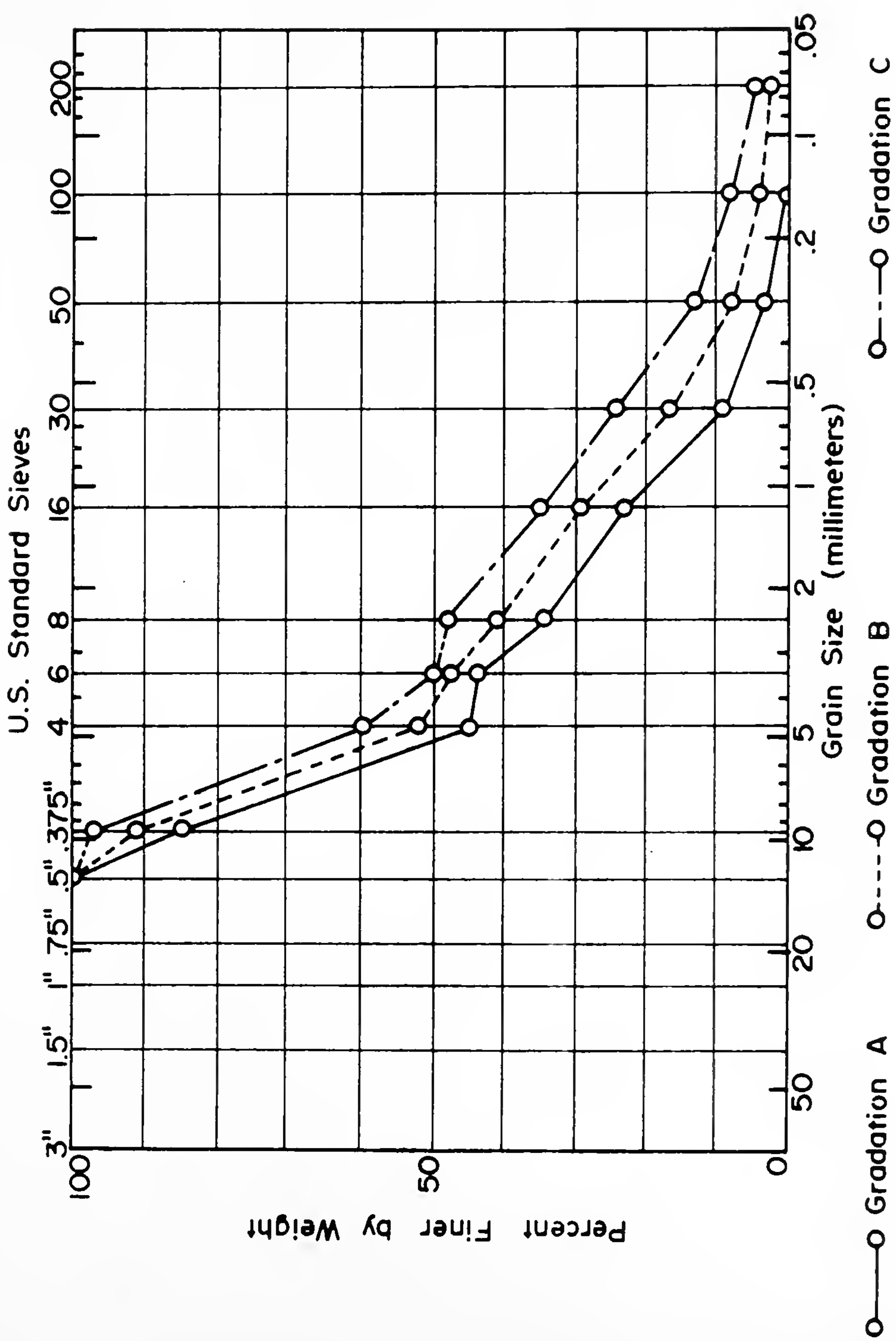


FIGURE 2 - SELECTED AGGREGATE GRADATIONS.

limit (gradation A), the middle point (gradation B) and the upper limit (gradation C) of the selected gradation band.

After drying and sieving, the aggregates were batched for each specimen by component fractions in accordance with the accumulative batch weight formula (based on the selected aggregate gradation). Prior to mixing, each individual batch of aggregate was thoroughly mixed, placed in the oven and heated to 325 ± 5 F (163 ± 3 C). The asphalt was heated separately to 300 ± 5 F (149 ± 3C). The aggregate and the asphalt were mixed in the Hobart electric mixer (Model N-50) for two minutes. The batch was then ready for compaction.

BITUMINOUS MIXTURE DESIGN

The gyratory testing machine (GTM) was used for compaction and testing. This machine (12) developed by the Waterways Experiment Station, Vicksburg, Mississippi, is based on a compaction technique devised by the Texas Highway Department.

The tentative ASTM testing method (1) was followed to compact the prepared mixture and to obtain its properties. Two specimens were prepared for each asphalt content of 5.0, 5.5, 6.0, 6.5 and 7.0 percent (by weight of aggregate) for limestone mixtures and 4.5, 5.0, 5.5, 6.0 and 6.5 percent (by weight of aggregate) for gravel mixtures. Aggregate gradation B was used for the design. The order of preparation of specimens was randomized (13).

Based on sample height, sample weight, percent asphalt, initial gyratory angle and gyrograph band width (Figure 3), calculations were made for the following properties (1):

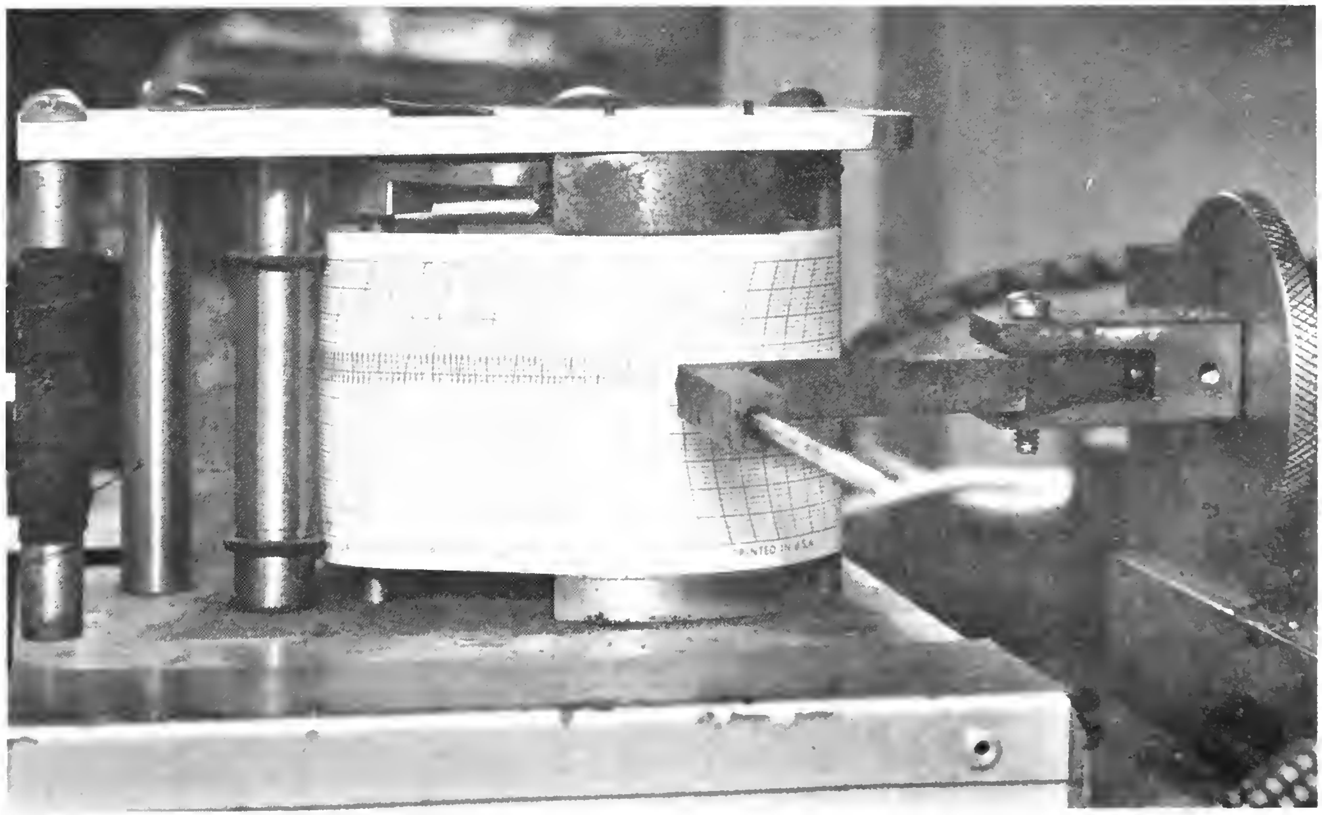


FIGURE 3- THE GYROGRAPH RECORDER.

1) Unit weight (total mix)

2) Unit weight (aggregate only)

3) Gyratory elasto-plastic index (GEPI)

$$\text{GEPI} = \frac{\text{Minimum intermediate gyrograph band width}}{\text{Initial gyratory angle}}$$

4) Gyratory stability index (GSI)

$$\text{GSI} = \frac{\text{Maximum gyrograph band width}}{\text{Minimum intermediate gyrograph band width}}$$

5) Gyratory compactibility index (GCI)

$$\text{GCI} = \frac{\text{Unit weight at 30 revolutions}}{\text{Unit weight at 60 revolutions}}$$

The calculated mixture property values are presented in Tables 5 and 6. These values are graphically represented in Figures 4 to 7. The main criteria for mixture design were the gyratory stability index, the unit weight (aggregate only) and the gyratory elasto-plastic index values. The other two properties were utilized only for reference and are not included in the following analysis.

The limestone mixture, as shown by the stability index plot of Figure 5, started losing its stability at 5.5 percent asphalt. This indicates that the design asphalt content from the stability standpoint should be about 5.5 percent. From the unit weight (aggregate only) point of view, the design value is about 6.5 percent (Figure 4). Taking an average value of the two, 6.0 percent was selected as the design asphalt content for the limestone mixture. From the elasto-plastic index plot (Figure 5), the design asphalt content should not exceed about 6.5 percent.

The gravel mixture started losing its stability at about 4.5 percent asphalt (Figure 7). As is evident from Figure 6, 5.5 percent asphalt gave the maximum value of unit weight (aggregate only). Consequently, the design asphalt content of 5.0 percent was selected for the gravel mixture design. This satisfied the elasto-plastic index requirement of a maximum of 6.0 percent asphalt for the design (Figure 7).

TABLE 5 - MIXTURE DESIGN COMPACTION AND SHEAR STRAIN PROPERTIES OF LIMESTONE MIXTURES

% Asphalt (by wt. of Agg.)	Unit Weight (Total Mix) pcf (Kg per cu m)		Unit Weight (Aggregate Only) pcf (Kg per cu m)		Gyratory Elasto-Plastic Index	Gyratory Stability Index	Gyratory Compactibility Index
	30 Rev	60 Rev	30 Rev	60 Rev			
5.0	135.8 (2175)	139.8 (2239)	129.3 (2071)	133.1 (2132)	1.35	1.00	0.971
5.5	137.0 (2195)	140.7 (2254)	129.9 (2081)	133.3 (2135)	1.39	1.00	0.973
6.0	137.9 (2209)	142.1 (2276)	130.2 (2086)	134.3 (2151)	1.40	1.03	0.970
6.5	139.2 (2230)	143.1 (2292)	130.7 (2094)	134.4 (2153)	1.40	1.06	0.972
7.0	137.8 (2207)	141.7 (2270)	128.8 (2063)	132.5 (2122)	1.42	1.18	0.972

TABLE 6 - MIXTURE DESIGN COMPACTION AND SHEAR STRAIN PROPERTIES OF GRAVFL MIXTURES

% Asphalt (by wt. of Agg.)	Unit Weight (Total Mix) pcf (Kg per cu m)		Unit Weight (Aggregate Only) pcf (Kg per cu m)		Gyratory Elasto-Plastic Index	Gyratory Stability Index	Gyratory Compactibility Index
	30 Rev	60 Rev	30 Rev	60 Rev			
4.5	145.5 (2329)	148.0 (2371)	139.2 (2230)	141.6 (2268)	1.46	1.00	0.983
5.0	146.7 (2350)	149.5 (2395)	139.7 (2238)	142.3 (2279)	1.52	1.02	0.981
5.5	147.6 (2364)	150.1 (2404)	140.0 (2243)	142.4 (2281)	1.50	1.03	0.984
6.0	147.7 (2366)	149.9 (2401)	139.4 (2233)	141.4 (2265)	1.52	1.11	0.986
6.5	147.8 (2368)	149.8 (2400)	138.8 (2223)	140.6 (2252)	1.66	1.46	0.987

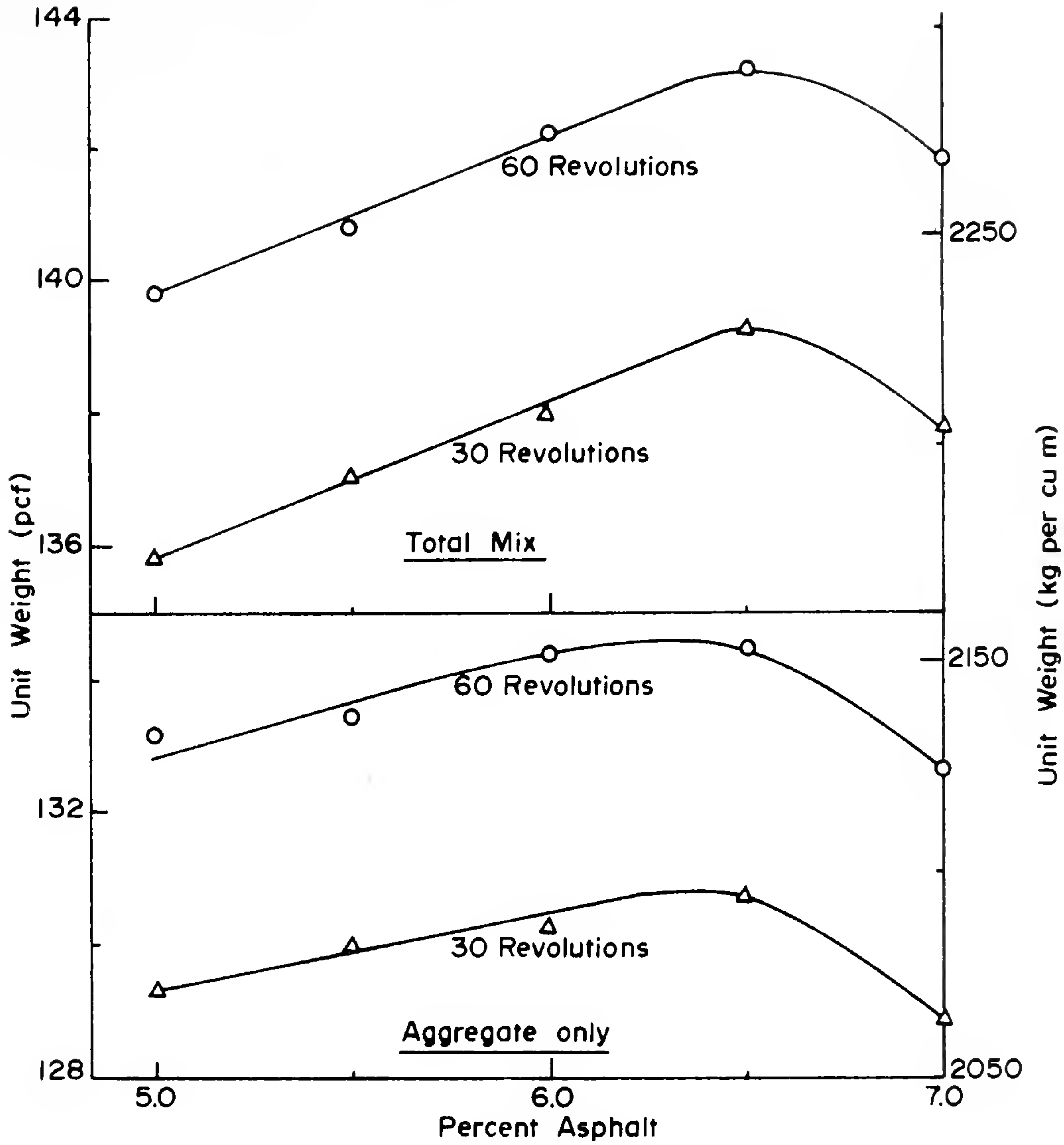


FIGURE 4 - UNIT WEIGHT Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURE DESIGN.

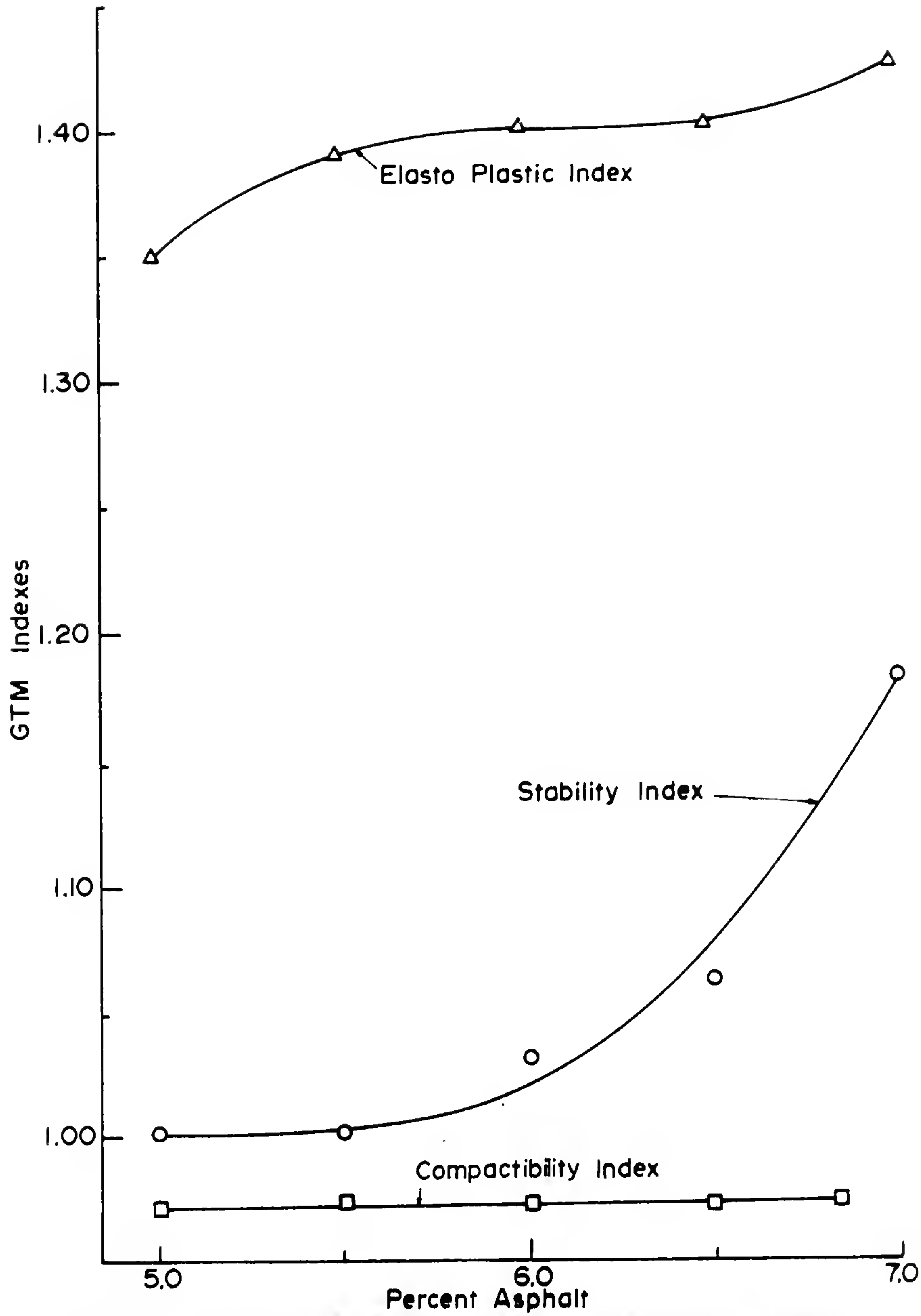


FIGURE 5 - GTM INDEXES Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURE DESIGN.

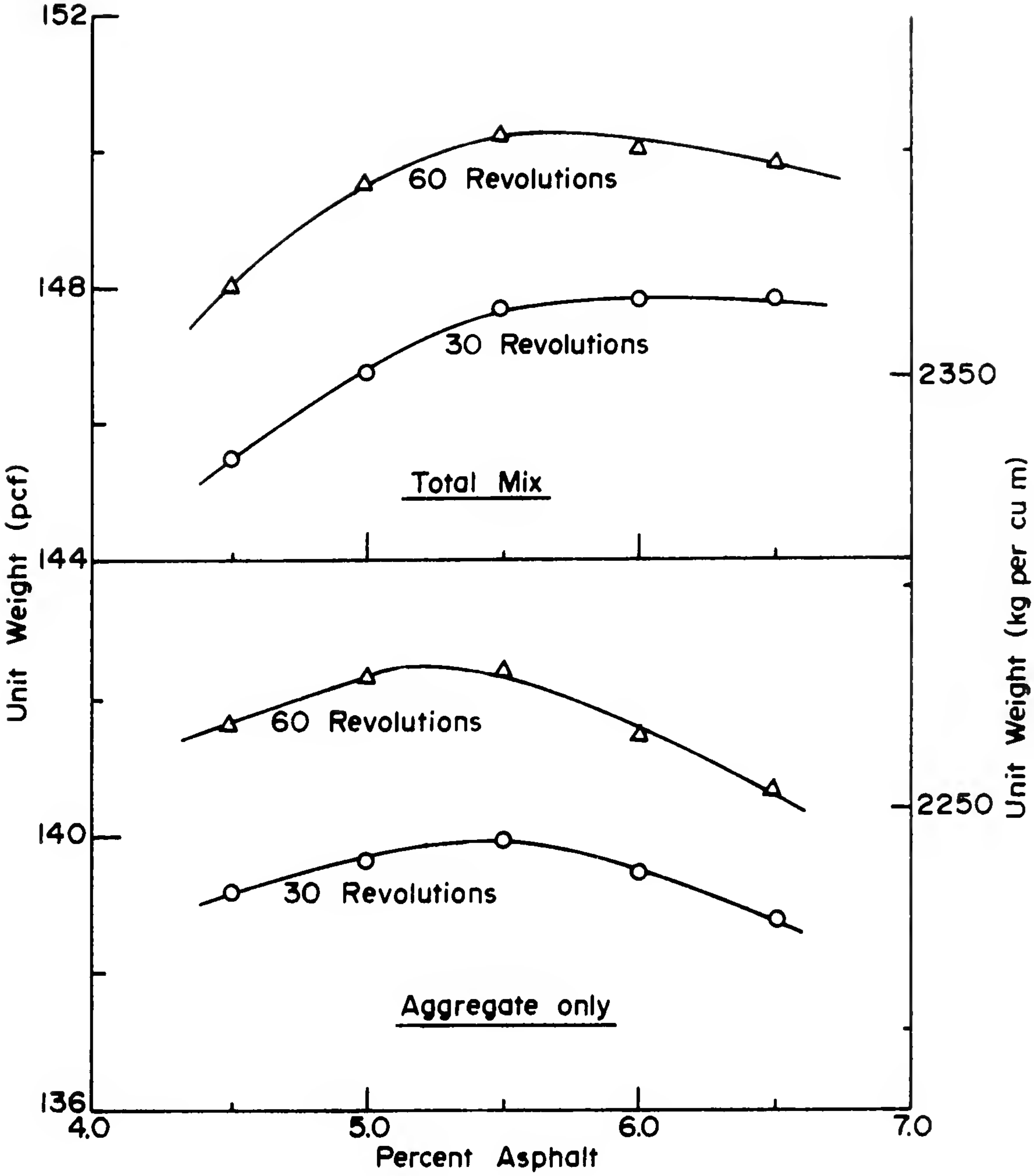


FIGURE 6 - UNIT WEIGHT Vs. PERCENT ASPHALT FOR GRAVEL MIXTURE DESIGN .

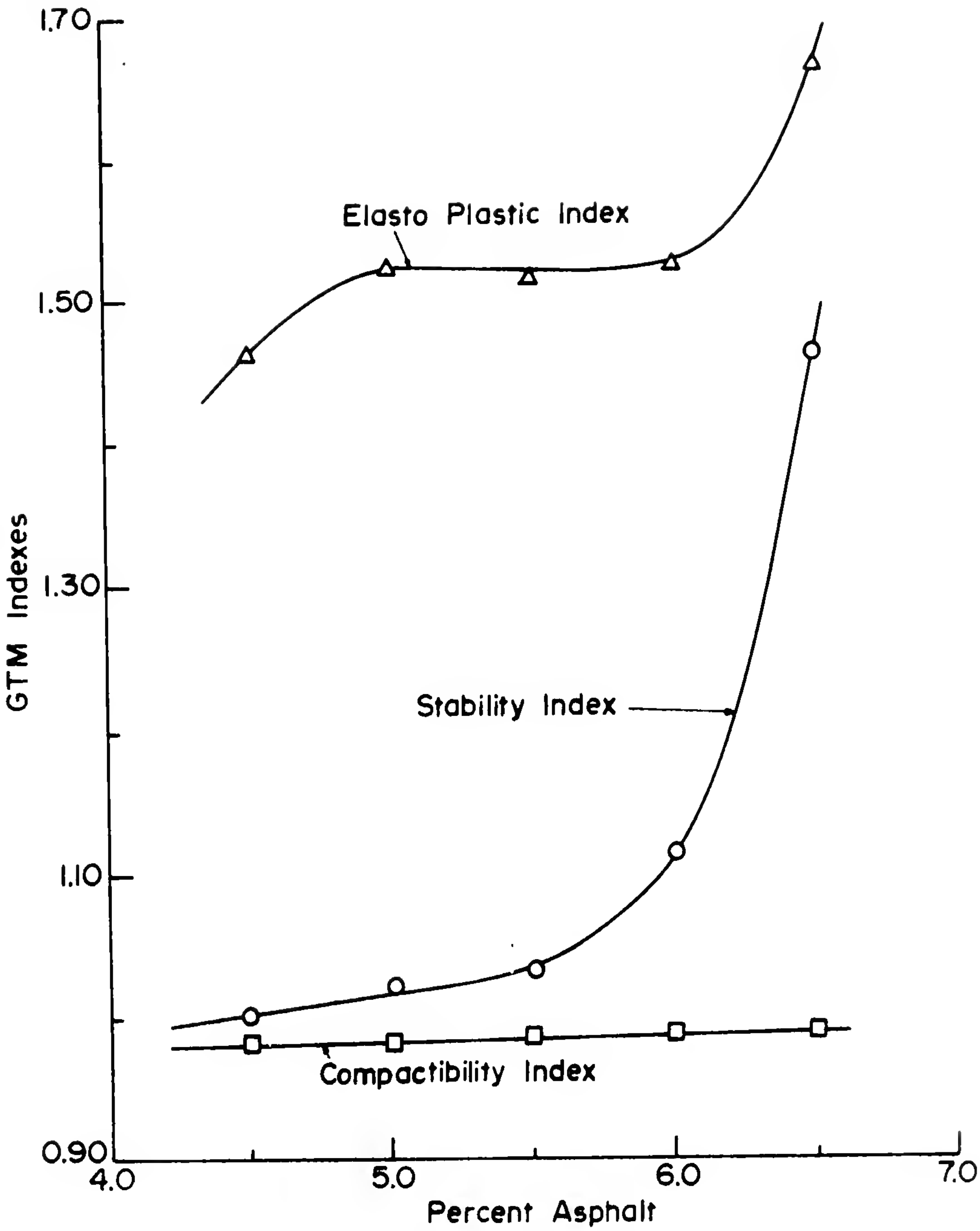


FIGURE 7 - GTM INDEXES Vs. PERCENT ASPHALT FOR GRAVEL MIXTURE DESIGN.

Therefore, for gradation B, the design asphalt contents for limestone and gravel mixtures were selected to be 6.0 percent and 5.0 percent respectively.

EVALUATION PROCEDURE AND TEST RESULTS

The limestone and gravel mixes of gradation B and design asphalt content were now subjected to the job mix formula tolerances. Each specimen prepared from a different batch was compacted using the GTM simulated field compaction technique followed by GTM simulated traffic densification testing. Mixture properties were calculated based on the observations made. This was done in order to study mixture behavior in terms of GTM properties under simulated traffic conditions and to examine if the difference in mixture property values resulting from variations in the designed gradation and percent asphalt as established by the tolerance limits of the job mix formula were significant. The data were also utilized in evaluating the design procedure.

Simulated Field Compaction

For limestone mixtures, duplicate specimens were prepared with asphalt contents of 5.7, 6.0 and 6.3 percent for each of the three gradations A, B and C (Figure 2). All eighteen specimens were prepared in a random order (13). For gravel mixes, asphalt contents of 4.7, 5.0, and 5.3 percent were used for each gradation A, B, and C. The order of preparation for these eighteen specimens was also randomized (13).

The above mixes were prepared using the same procedure described earlier under the heading 'Materials and Mixture Preparation'. Specimen compaction was achieved by using a GTM procedure which provides for simulated steel wheel roller compaction. The method is briefly described as follows (7): The upper roller of the gyratory testing machine was changed from a fixed to an air roller. The GTM was set for a 3 degree angle of gyration, 100 psi (7.03 Kgf per sq cm) ram pressure and a 15.0 psi (1.06 Kgf per sq cm) air roller pressure. The chuck heater, adjusted to 140 F (60C), was switched on one hour before the compaction of the first specimen.

Simulated Traffic Densification

Next, the compacted specimen was subjected to simulated traffic densification using the GTM. The GTM settings were readjusted to a 2 degree angle of gyration, 20 psi (1.41 Kgf per sq cm) air roller pressure, and 100 psi (7.03 Kgf per sq cm) ram pressure (8).

In order to establish the heater settings, temperatures were measured at the center of the specimen, at the circumfrential surface of the specimen in contact with the mold, and of the mold chuck at regular intervals of time (Figure 8). It was observed that the temperature stabilized at 131 F (55.0 C) and 142 F (61.0 C) in the center and at the surface, respectively, when the temperature of the mold was set to 150 F (65.5 C). Thus, this temperature setting of the mold chucks kept the specimen temperature close to the densification testing temperature of 140 F (60 C).

Key to details of Figure 8

A. Front mold chuck

B. Measures temperature at the circumfrential surface of the specimen

C. Measures temperature of the front mold chuck

D. Measures temperature at the center of the specimen

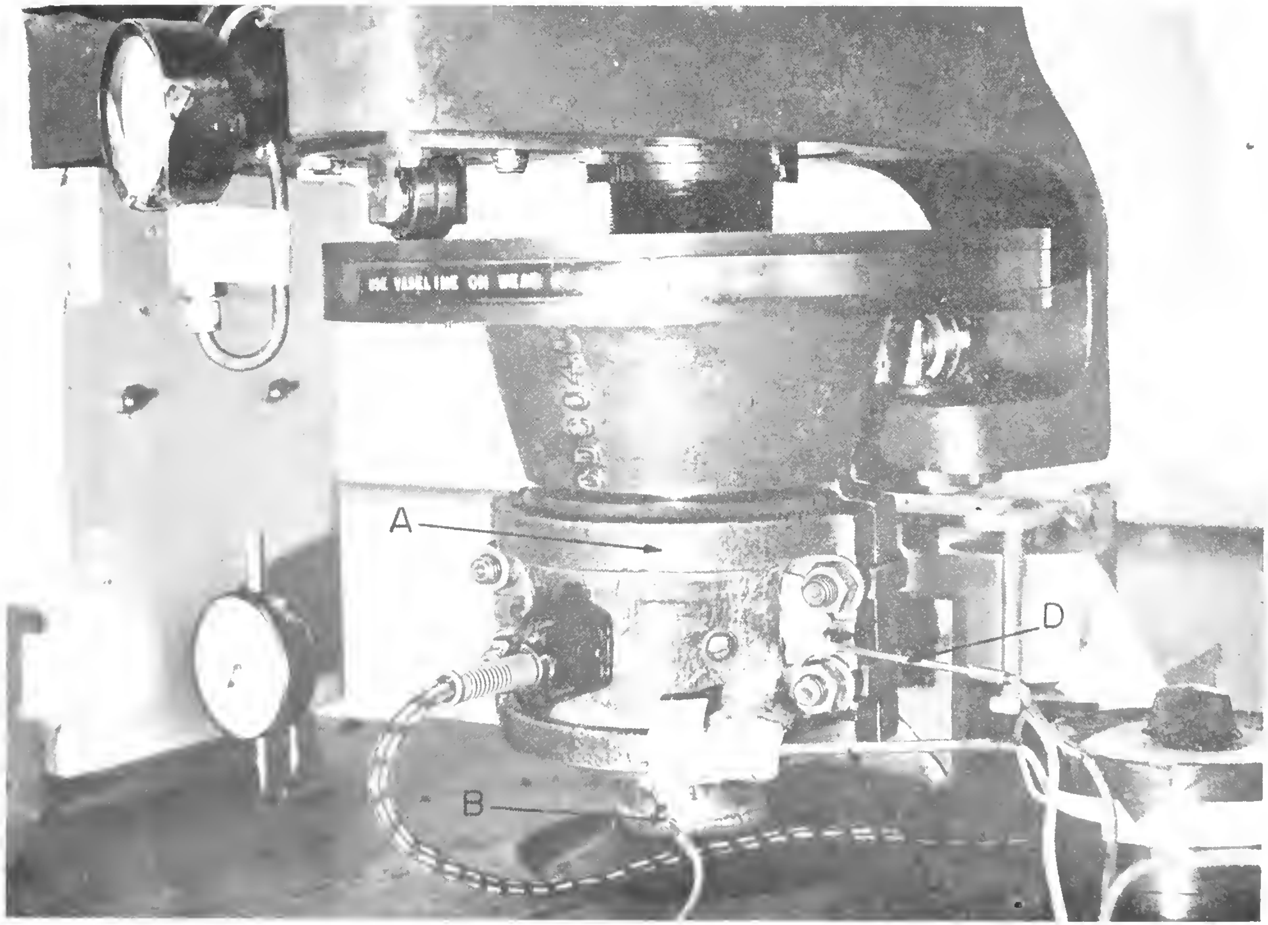


FIGURE 8 - TEMPERATURE MEASUREMENTS OF THE SPECIMEN.

The mold containing the compacted specimen, kept in the oven at 140 F (60 C) for over night, was removed and placed in the GTM. After applying the vertical pressure, the mold was clamped in the GTM mold chuck. The initial specimen height was recorded and the gyrograph recorder switch was turned on. The roller carriage was then actuated. The testing was stopped at 50, 100, 200, 300, 500, 750 and 1000 revolutions to record the sample height and air roller pressure readings. At the end of 1000 revolutions, the mold was removed from the GTM and the specimen was extruded. The specimen was weighed after it had cooled to room temperature.

Mixture Property Calculations

Using specimen height, specimen weight, percent asphalt, air roller pressure and gyrograph band widths, calculations were made to obtain the following properties for each of the thirty-six specimens representing the eighteen mixtures:

1) Unit weight (total mix)
2) Unit weight (aggregate only)
3) Gyratory shear value (G_s)

$$G_s = \frac{2.1p}{h} (.028)$$

Where G_s = Gyratory shear value

p = Air roller pressure in psi (Kgf per sq cm)

h = Height of the specimen in inches (cm)

4) Gyratory stability index (GSI^x_{50})

$$GSI^x_{50} = \frac{\text{Gyrograph width at x revolutions of densification}}{\text{Gyrograph width at 50 revolutions of densification}}$$

5) Gyratory compactibility index (GCI^x_{50})

$$GCI^x_{50} = \frac{\text{Unit weight of total mix at x revolutions of densification}}{\text{Unit weight of total mix at 50 revolutions of densification}}$$

Figures A1 to A10 (Appendix A) show the averages of these mixture property values plotted against number of revolutions. Mixture property values vs percent asphalt content plots at 500 and 1000 revolutions are shown in Figures A11 to A20 (Appendix A). Since the analyses made on the basis of these plots alone can be misleading, the entire mixture property data were also analyzed statistically (14). Summaries of the statistical results are presented in Tables 7 to 12 and Figures 9 to 12.

ANALYSIS OF TEST RESULTS

The calculated mixture properties were utilized to study the following factors in order:

Influence of simulated traffic densification on the mixture properties

Job mix formula and the tolerance limits

Evaluation of the GTM design method

Influence of Simulated Traffic Densification on the Mixture Properties

Figures A1 through A10 illustrate changes in mixture properties occurring with increasing simulated traffic densification. Analysis of variance tests (ANOVA) were conducted on the mixture property values to statistically analyze the overall effect of gradation, percent asphalt and number of revolutions. The results are summarized in Tables 7 and 8 and in Tables 9 and 10 for limestone and gravel mixes, respectively. These tables also present the effects due to interaction between the three factors, gradation, percent asphalt and number of revolutions. These interaction results are not utilized in this analysis since they were not of much importance to the present study.

Examining the limestone mixtures first, the unit weight (total mix and aggregate only) values increase with increasing number of revolutions (Figures A1 & A2). The curves have more slope initially, then tend to flatten as the number of revolutions increases. Use of different percentages of asphalt content tends to shift the entire curve but does not change its general shape. ANOVA results (Tables 7 & 8), up to both 500 and 1000 revolutions, show that all of the three variables, gradation, percent asphalt and number of revolutions, significantly (at the 5 percent level) affected the property values except for percent asphalt which was not significant up to 500 revolutions for unit weight (aggregate only).

TABLE 7 - INFLUENCE OF GRADATION, PERCENT ASPHALT AND REVOLUTION ON LIMESTONE MIXTURE PROPERTIES UP TO 500 REVOLUTIONS (RESULTS OF ANALYSIS OF VARIANCE TEST)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Accept H_o	Reject H_o	Reject H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o
IL	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Accept H_o	Reject H_o

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

TABLE 8 - INFLUENCE OF GRADATION, PERCENT ASPHALT AND REVOLUTION ON LIMESTONE MIXTURE PROPERTIES UP TO 1000 REVOLUTIONS (RESULTS OF ANALYSIS OF VARIANCE TEST)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o
IL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

The gyratory shear and gyratory stability index values (Figures A3 & A4) increased in general (i.e., the mixture started losing its stability) with increasing number of revolutions. According to ANOVA results (Tables 7 & 8), all of the three variables, gradation, percent asphalt and number of revolutions, significantly affect the gyratory stability index value, but the gyratory shear value is only affected by number of revolutions. The gyratory compactibility index value decreases rapidly (i.e. increase in densification) initially and then tends to flatten with increasing number of revolutions (Figure A5). All of the three variables affect the gyratory compactibility index value significantly as is indicated by ANOVA results (Tables 7 & 8).

With respect to the gravel mixtures, unit weight (total mix and aggregate only) values increase rapidly initially followed by a flattening of the curve with increasing number of revolutions (Figures A6 & A7). ANOVA results show (Tables 9 & 10) that gradation, percent asphalt and number of revolutions significantly affect these values except for percent asphalt which has no significant influence on the unit weight (aggregate only) value.

The gyratory shear value does not increase appreciably but the gyratory stability index value increases with increase in number of revolutions (Figures A8 & A9). ANOVA results (Tables 9 & 10) show that all of the three variables, gradation, percent asphalt and number of revolutions significantly affect these properties. The gyratory compactibility index value decreases with increasing number of revolutions (Figure A10). ANOVA results (Tables 9 & 10) show that

TABLE 9 - INFLUENCE OF GRADATION, PERCENT ASPHALT AND REVOLUTION ON GRAVEL MIXTURE PROPERTIES UP TO 500 REVOLUTIONS (RESULTS OF ANALYSIS OF VARIANCE TEST)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^{x}_{50})	Gyratory Compactibility Index (GCI^{x}_{50})
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Reject H_o	Reject H_o	Accept H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

TABLE 10 - INFLUENCE OF GRADATION, PERCENT ASPHALT AND REVOLUTION ON GRAVEL MIXTURE PROPERTIES UP TO 1000 REVOLUTIONS (RESULTS OF ANALYSIS OF VARIANCE TEST)

Factor	Unit Weight (Total Mix)	Unit Weight Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

only asphalt content is not significant in affecting this mixture property up to 500 revolutions, but it also becomes significant when evaluated up to 1000 revolutions.

The above discussion indicates that the gyratory testing machine is sensitive enough to predict mixture behavior at any level of traffic densification for both limestone and gravel types of mixes. Therefore, it can be concluded that the use of the gyratory testing machine is both feasible and practical in the evaluation of bituminous mixes with respect to densification.

Job Mix Formula and the Tolerance Limits

In this section an analysis is presented to demonstrate that even if the mixture composition is within the tolerance limits, the mixture property values may be significantly different with respect to designed mixture property values.

The properties of the specimens with all possible combinations of gradations A, B and C with asphalt contents of 5.7, 6.0 and 6.3 percent for limestone, and 4.7, 5.0 and 5.3 percent for gravel, were considered for this investigation. Two levels of densification, one at 500 gyratory revolutions and the other at 1000 gyratory revolutions were selected for the analysis. Figures A11 through A15 and A16 through A20 present the plots of mixture properties against percent asphalt at 500 and 1000 revolutions for limestone and gravel mixtures, respectively.

ANOVA tests were carried out on the mixture property values to determine if there was any significant difference (at the 5 percent level) between the values due to variations in gradation and percnet asphalt (Tables 11 & 12). The plots were not analyzed if the differences were found to be non-significant. The rest of the plots were studied and another statistical test called the Newman-Keuls Sequential Range Test (NKSRT) was conducted on these mixture property values to test for significance (at the 5 percent level) between each mixture composition (Figures 9 to 12).

On examining the limestone mixture property values, at 500 revolutions the NKSRT results (at 5 percent level) indicate (Figure 9) that if either gradation A or C was used instead of gradation B, both unit weight (total mix) and unit weight (aggregate only) values were significantly affected. Values were higher for gradation C and lower for gradation A as compared to gradation B (Figures A11 and A12). If 5.7 percent asphalt content was used instead of 6.0 percent, the unit weight (total mix) values were significantly affected and were lower than the designed value (Figures 9 and A11). Use of 6.3 percent asphalt did not significantly affect the designed value. Unit weight (aggregate only) values were not significantly affected if either 5.7 percent or 6.3 percent asphalt was used. The same trend was observed for both unit weight (total mix) and unit weight (aggregate only) at 1000 revolutions (Figures 10, A11 and A12).

The gyratory shear and gyratory compactibility index values of limestone mixtures (Figures A13 and A15) were not significantly affected

TABLE 11 - INFLUENCE OF GRADATION AND PERCENT ASPHALT ON LIMESTONE MIXTURE PROPERTIES AT 500 AND 1000 REVOLUTIONS (RESULTS OF ANALYSIS OF VARIANCE TEST)

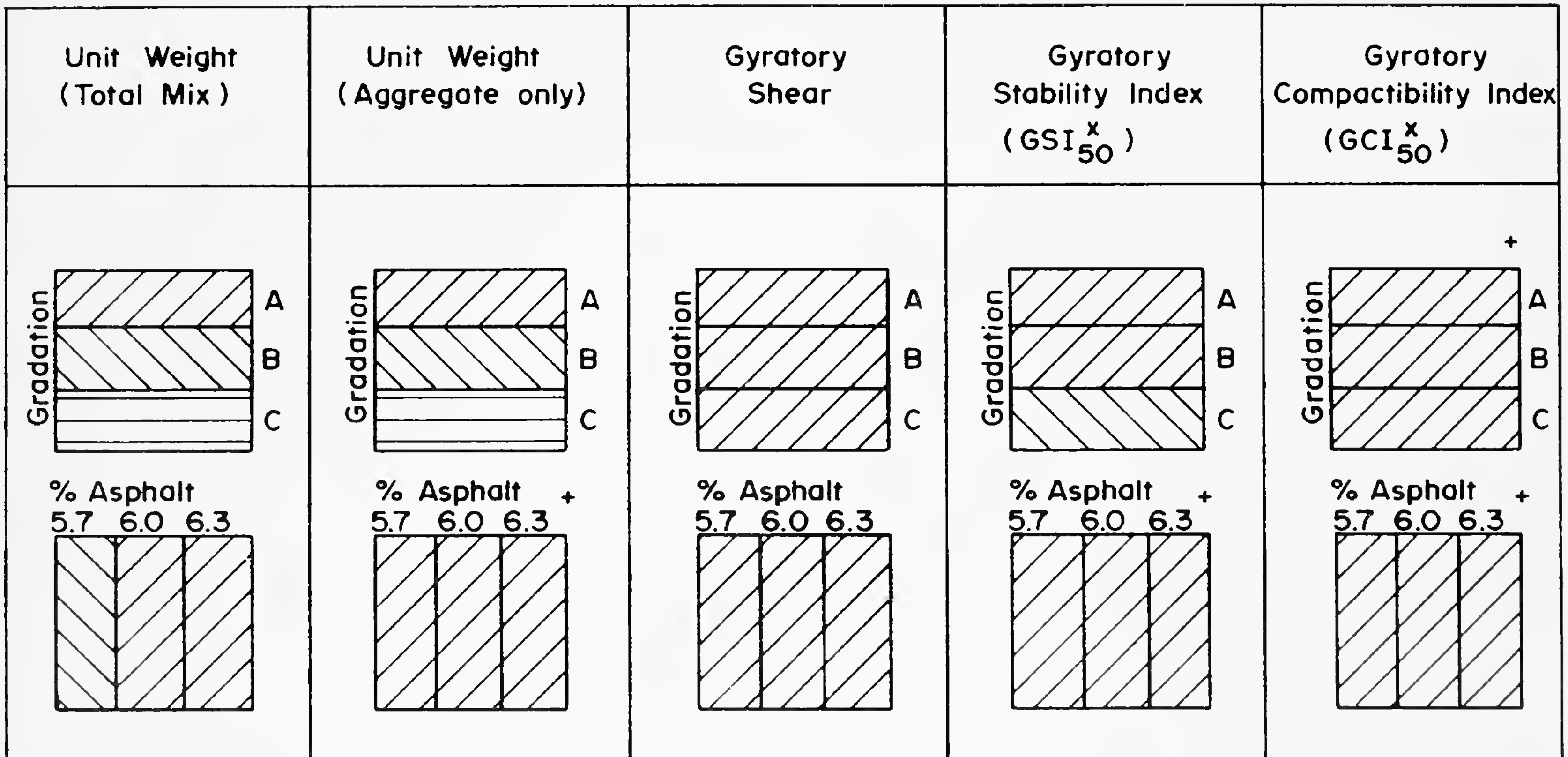
Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^{x}_{50})	Gyratory Compactibility Index (GCI^{x}_{50})
AT 500 REVOLUTIONS					
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o
AT 1000 REVOLUTIONS					
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

TABLE 12 - INFLUENCE OF GRADATION AND PERCENT ASPHALT ON GRAVEL MIXTURE PROPERTIES AT 500 and 1000 REVOLUTIONS (RESULTS OF ANALYSIS OF VARIANCE TEST)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
			AT 500 REVOLUTIONS		
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
			AT 1000 REVOLUTIONS		
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o

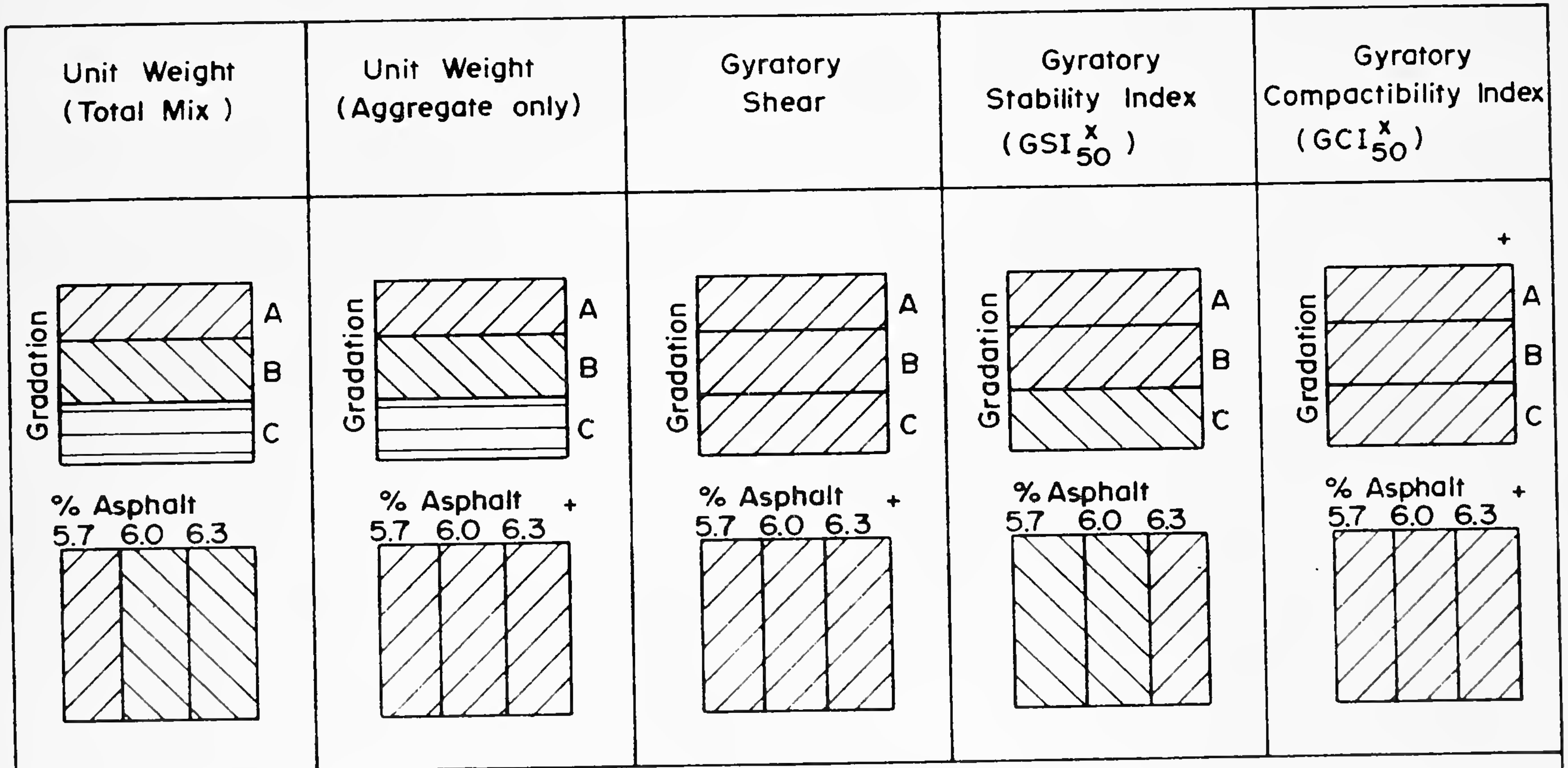
H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)



+ Significance between the means could not be ranked

NOTE : Difference in values between specimens incorporating the same symbol are not significant at 5% level, for each mixture property.

FIGURE 9 - NEWMAN-KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR LIMESTONE MIXTURE PROPERTIES (AT 500 REVOLUTIONS).



+ Significance between the means could not be ranked

NOTE : Difference in values between specimens incorporating the same symbol are not significant at 5% level, for each mixture property.

FIGURE 10 - NEWMAN-KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR LIMESTONE MIXTURE PROPERTIES (AT 1000 REVOLUTIONS).

(NKSRT results, Figures 9 and 10) at both 500 and 1000 revolutions by variations in gradation and asphalt content. Examining the NKSRT results (Figures 9 and 10) for gyratory stability index values, only gradation C had a significant affect on the values at both 500 and 1000 revolutions resulting in loss in stability (Figure A14). The mixtures with 6.3 percent asphalt content showed significant loss in stability at 1000 revolutions, whereas at 500 revolutions the loss was not significant (Figures 9, 10 and A14). The stability values were not significantly affected by using 5.7 percent asphalt content.

The above analysis on limestone mixtures indicates that the use of gradation C instead of gradation B will result in significant gain in unit weight (total mix and aggregate only) with a loss in stability at both 500 and 1000 revolutions. On the other hand, the use of gradation A will produce a loss in unit weight (total mix and aggregate only) without any gain in stability at both 500 and 1000 revolutions. This shows that strict control of gradation should be exercised. Use of 6.3 percent asphalt content instead of 6.0 percent will result in loss in stability at higher densification effort (1000 revolutions) without any gain in other properties. If 5.7 percent asphalt content is used, loss in unit weight (total mix) will result without any gains elsewhere. This indicates that leniency in control can be exercised towards the higher side of the asphalt content only in cases when traffic intensity is low. A strict check should be made on the lower side of the designed value since the use of less asphlt (within job mix tolerances) has no advantage.

Analyzing gravel mixture results (Figures 11, 12 A16 and A17), the use of gradation A instead of gradation B resulted in significant loss in unit weight (total mix and aggregate only) at 500 revolutions. This loss was not appreciable for unit weight (aggregate only) at 1000 revolutions. No. appreciable unit weight loss was observed when gradation C was used. Use of 4.7 percent or 5.3 percent asphalt content did not indicate any significant change in unit weight (total mix and aggregate only) values at 500 and 1000 revolutions.

The gyratory shear results on gravel mixtures (Figures 11, 12 and A18) indicated in general that coarse gradation and low percent asphalt combinations were significantly different as compared to fine gradation and high percent asphalt combinations. The same trend was observed for both gyratory stability index and gyratory compactibility index values (Figures 11, 12, A19 and A20).

Based on the above analysis, it can be observed that the use of the finer side of the designed gradation will result in loss in stability and loss in shear strength of the gravel mixture without any appreciable gain in the unit weight (total mix and aggregate only). Therefore under all circumstances a strict control should be exercised on the finer side of the designed gradation. Use of the coarser side of the designed gradation at low densifying effort (500 revolutions) will result in loss in unit weight (total mix and aggregate only) without any appreciable increase in shear strength, but the stability of the mixture will be improved. With increase in densifying effort (1000 revolutions), there is gain in unit weight (aggregate only) but the shear strength is reduced. The stability value is unaffected. This indicates that leniency may be exercised on the coarser side if higher stability is desired.

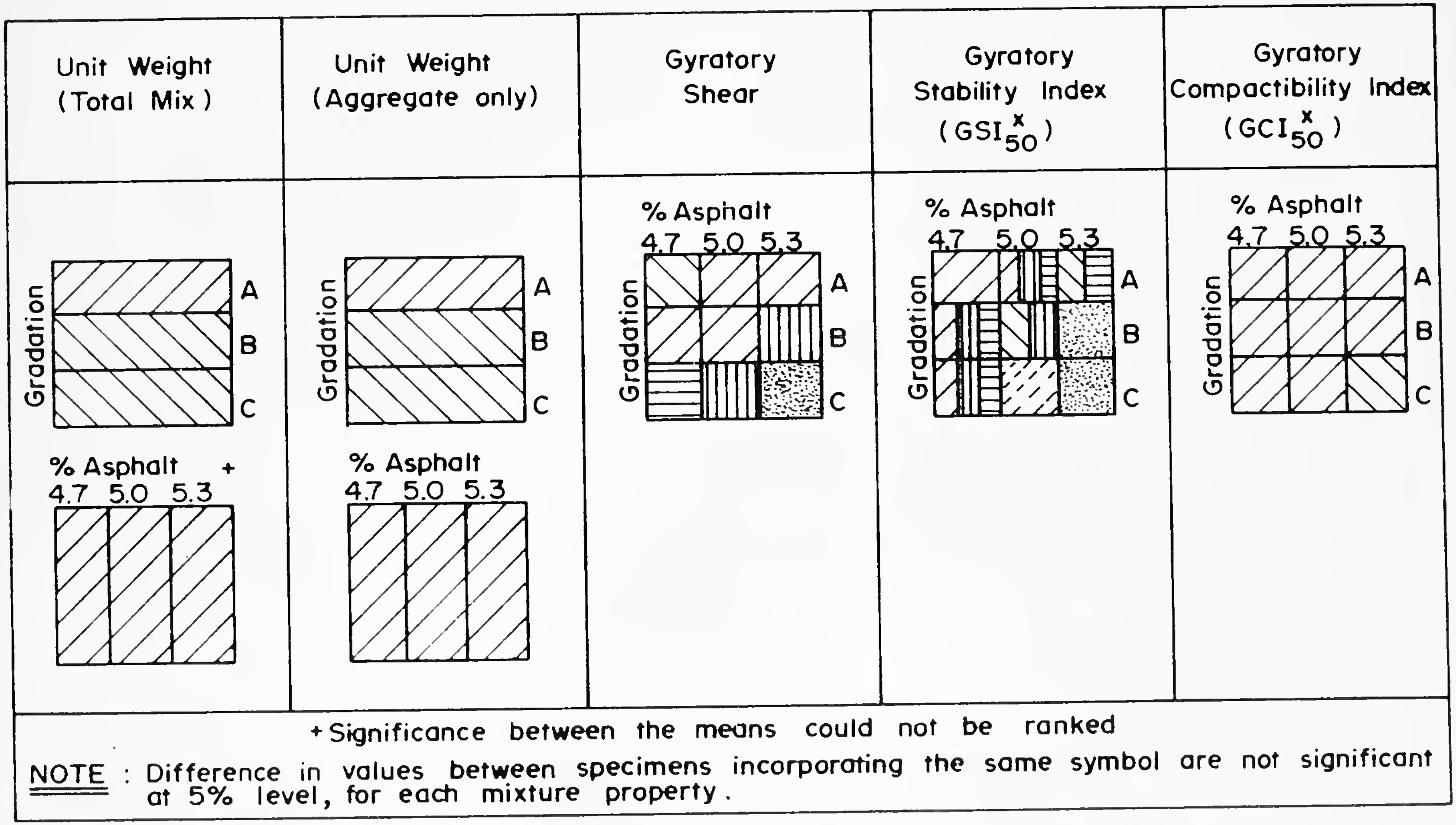
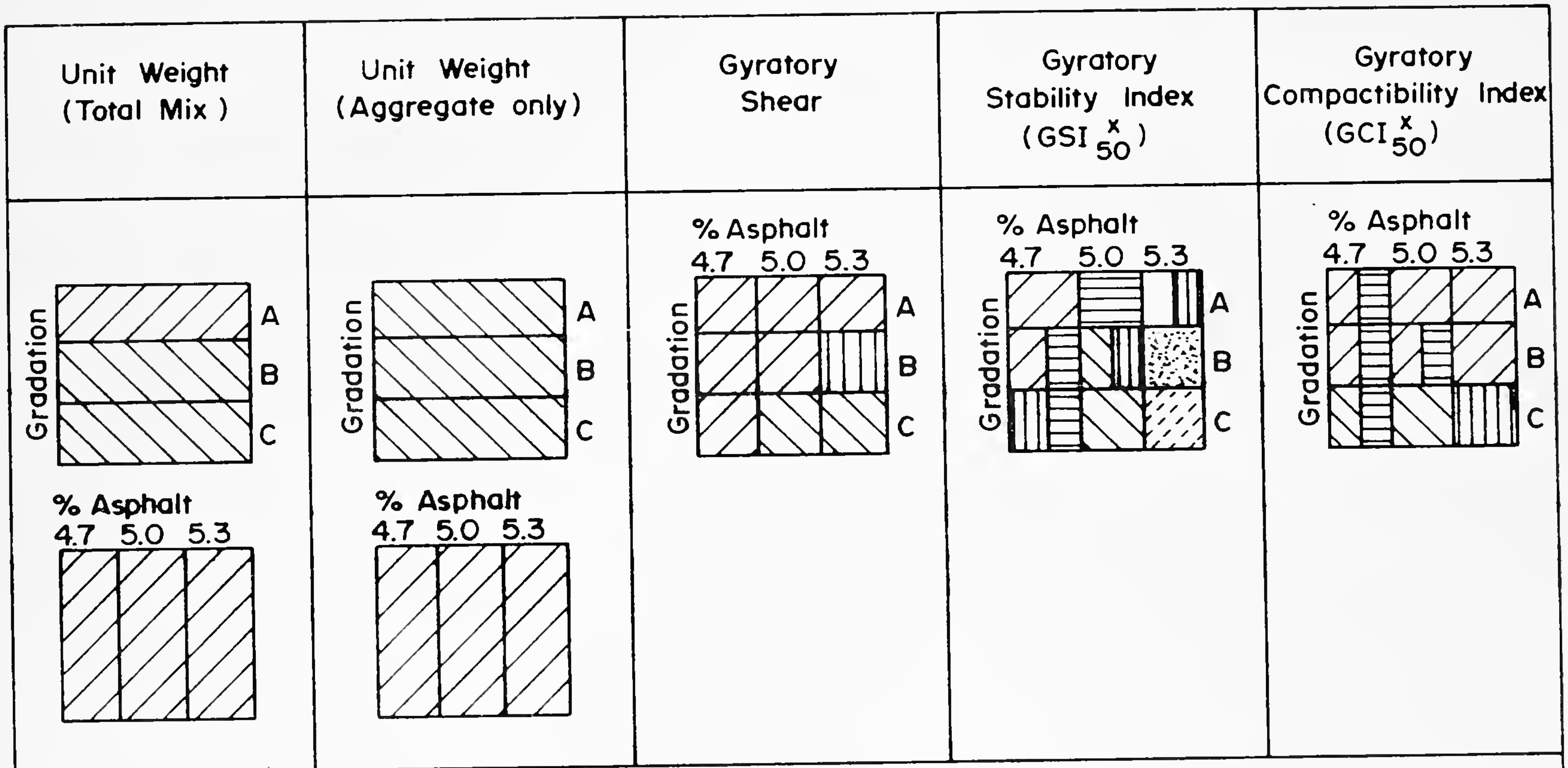


FIGURE II - NEWMAN - KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR GRAVEL MIXTURE PROPERTIES (AT 500 REVOLUTIONS).



NOTE : Difference in values between specimens incorporating the same symbol are not significant at 5% level, for each mixture property.

FIGURE 12 - NEWMAN - KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR GRAVEL MIXTURE PROPERTIES (AT 1000 REVOLUTIONS).

Use of asphalt on the higher side of the designed value will not give any improved unit weight (total mix and aggregate only) but will result in loss of shear strength and loss in stability. This indicates that strict control should be exercised on the higher side of the designed asphalt content. In case the quantity of asphalt used is on the lower side of the designed value, no appreciable loss in unit weight (total mix and aggregate only) will result but the shear strength and stability of the mixture will improve at low densification levels (500 revolutions). With increased densification effort (1000 revolutions), the shear strength will be reduced. So leniency in control on the lower side of the designed asphalt content should only be exercised when high stability is desired.

The above analysis indicates that the gyratory testing machine is sensitive enough to study the changes in mixture properties caused by small variations in gradation and asphalt content.

Evaluation of the Design Method

In this section, an analysis is made to determine if the selected design values were appropriately chosen for both limestone ang gravel mixes. The analysis is based on the test results obtained by subjecting gradation B limestone and gravel mixes to the tolerance limits of $\pm$ 0.3 percentage points of asphalt. Accordingly, the properties of the limestone mixes having compositions B5.7, B6.0, B6.3 and gravel mixes having compositions B4.7, B5.0 B5.3 obtained earlier (under heading 'Mixture Property Calculations') were utilized in this study. (The

letter designates gradation and the figure represents percent asphalt content.) Two levels of densification, one at 500 revolutions and the other at 1000 revolutions, were selected and the property values of the specimens were compared at each level.

Examining test results for limestone mixtures first, NKSRT results for unit weight (total mix) show (Figures 9 and 10) that the difference in the values of specimens with 6.0 percent and 6.3 percent asphalt content are not significant, but both give values significantly different to the specimen having 5.7 percent asphalt. No significant difference was observed for the unit weight (aggregate only) value. The difference in gyratory shear, gyratory stability index and gyratory compactibility index values was insignificant with respect to variations in percent asphalt content with an exception that, at 1000 revolutions, the gyratory stability index plot (Figure A14) shows considerable loss in stability for the specimen with 6.3 percent asphalt as compared to specimens having 5.7 and 6.0 percent asphalt. The same analysis is made by NKSRT (Figure 10).

Examining the overall picture for limestone mixes, if asphalt content is increased from 6.0 percent to 6.3 percent, there is no significant gain in unit weight (total mix and aggregate only), but the loss in stability is appreciable. By reducing the asphalt content to 5.7 percent, there will be no gains whatsoever. Hence, it can be concluded that 6.0 percent asphalt is the correct optimum asphalt content for the limestone mixture design.

With respect to gravel mixture design, no significant difference in unit weight (total mix and aggregate only) properties is observed with respect to variations in percent asphalt content (Figures 11 and 12). The NKSRT indicates that for gyratory shear (Figure A18) the values at 4.7 percent and 5.0 percent asphalt are nearly the same, but each of them is significantly different from the specimen having 5.3 percent asphalt (Figures 11 and 12). The same general results were obtained for the gyratory stability index value except that at 1000 revolutions (Figure 12) all three percent asphalt contents gave values significantly different from each other. The gyratory compactibility index values were not significantly different at different percent asphalt contents (Figures 11 & 12).

In short, this analysis for gravel mixes indicates that increase in asphalt content from 5.0 percent to 5.3 percent will reduce the shear value and will result in loss of stability with no increase in unit weight. Decreasing the asphalt content to 4.7 percent has no advantage except that there will be a small gain in stability after a long period of simulated traffic densification. Thus 5.0 percent asphalt content as the optimum design value appears to be justified for the gravel mixture.

The above analyses for both limestone and gravel mixes demonstrate that 1) the tentative ASTM testing method (1) produces compaction and shear strain properties which can be used to design both limestone and gravel mixes, 2) the authors' interpretation of the mixture properties as applied to the design of bituminous mixtures seems justified, and

3) the gyratory testing machine can be used successfully to design bituminous mixes.

CONCLUSIONS

These conclusions are based on the results of the experimental data and their discussion as presented. It should be noted that the conclusions given here are applicable to the materials and the testing procedures of this specific research only and may not be extended beyond these limits without the appropriate verification.

1. Bituminous mixtures can be effectively designed based on their compaction and shear strain properties obtained by means of the gyratory testing machine using the tentative ASTM testing method.
2. The gyratory testing machine can be used as a laboratory traffic simulation device to measure changes in compaction and shear strain properties of bituminous mixtures to be expected when they are placed in service.
3. The sensitivity of bituminous mixtures with respect to variations in gradation and asphalt content can be studied through the use of the gyratory testing machine. This in turn can help modify the job mix formula tolerances to suit particular field conditions.

REVIEW OF LITERATURE

1. Tentative Method of Test for Compaction and Shear Strain Properties of Hot Bituminous Mixtures by means of the U.S. Corps of Engineers Gyratory Testing Machine using Fixed Roller. In process of development by Subcommittee D04.20 of Committee D-4, American Society for Testing Materials, Philadelphia, Pa.

2. Ortolani, L. and Sandberg, H. A. Jr., "The Gyratory-Shear Method of Molding Asphaltic Concrete Test Specimens, Its Development and Correlation with Field Compaction Methods, A Texas Highway Department Standard Procedure," Proceedings, Association of Asphalt Paving Technologists, Vol. 21 (1952).

3. Development of the Gyratory Testing Machine and Procedures for Testing Bituminous Paving Mixtures, Technical Report No. 3-595, U. S. Army Engineer Waterways Experimental Station, February, 1962.

4. Mc Rae, J. L. and Foster, C. R., "Theory and Application of a Gyratory Testing Machine for Hot-Mix Bituminous Pavement," American Society for Testing Materials, Special Technical Publication No. 252 (1959).

5. Busching, H. W., "Stability Relationships of Gyratory Compacted Bituminous Mixtures," M.S. Thesis, Purdue University, June, 1963.

6. Hughes, R. E., "Use of a Gyratory Testing Machine to Apply Simulated Traffic to Bituminous Concrete," M.S. Thesis, Purdue University, January, 1964.

7. Ruth, B. E. and Schaub, J. H., "Gyratory Testing Machine Simulation of Field Compaction of Asphaltic Concrete," Proceedings, Association of Asphalt Paving Technologists, Vol. 35 (1966).

8. Ruth, B. E. and Schaub, J. H., "A Design Procedure for Asphaltic Concrete Mixtures," Proceedings, Association of Asphalt Paving Technologists, Vol. 37 (1968).

9. Potts, C. F., "The Simulation of Traffic with the Gyratory Testing Machine," M.S. Thesis, West Virginia University, 1967.

10. Indiana State Highway, Standard Specifications, 1971, Indiana State Highway Commission, Indianapolis, Indiana.

11. Kumar, Arun, "Evaluation of Bituminous Mixtures Using the Gyratory Testing Machine," M.S. Thesis, Purdue University, August, 1973.

12. McRae, J. L., Gyratory Testing Machine Technical Manual, Engineering Developments Company, Inc., Viksburg, Mississippi, 1965, Revised September, 1970.

13. Snedecor, G. W., Everyday Statistics, Wm. C. Brown Company, Dubuque, Iowa, 1950.

14. Ostle, Bernard, Statistics in Research, The Iowa State University Press, Ames, Iowa, 1963.

15. Mix Design Methods for Asphalt Concrete, Manual Series No. 2, Second Edition, The Asphalt Institute, February, 1962.

16. The Asphalt Handbook, Manual Series No. 4, The Asphalt Institute, April, 1965.

APPENDIX A

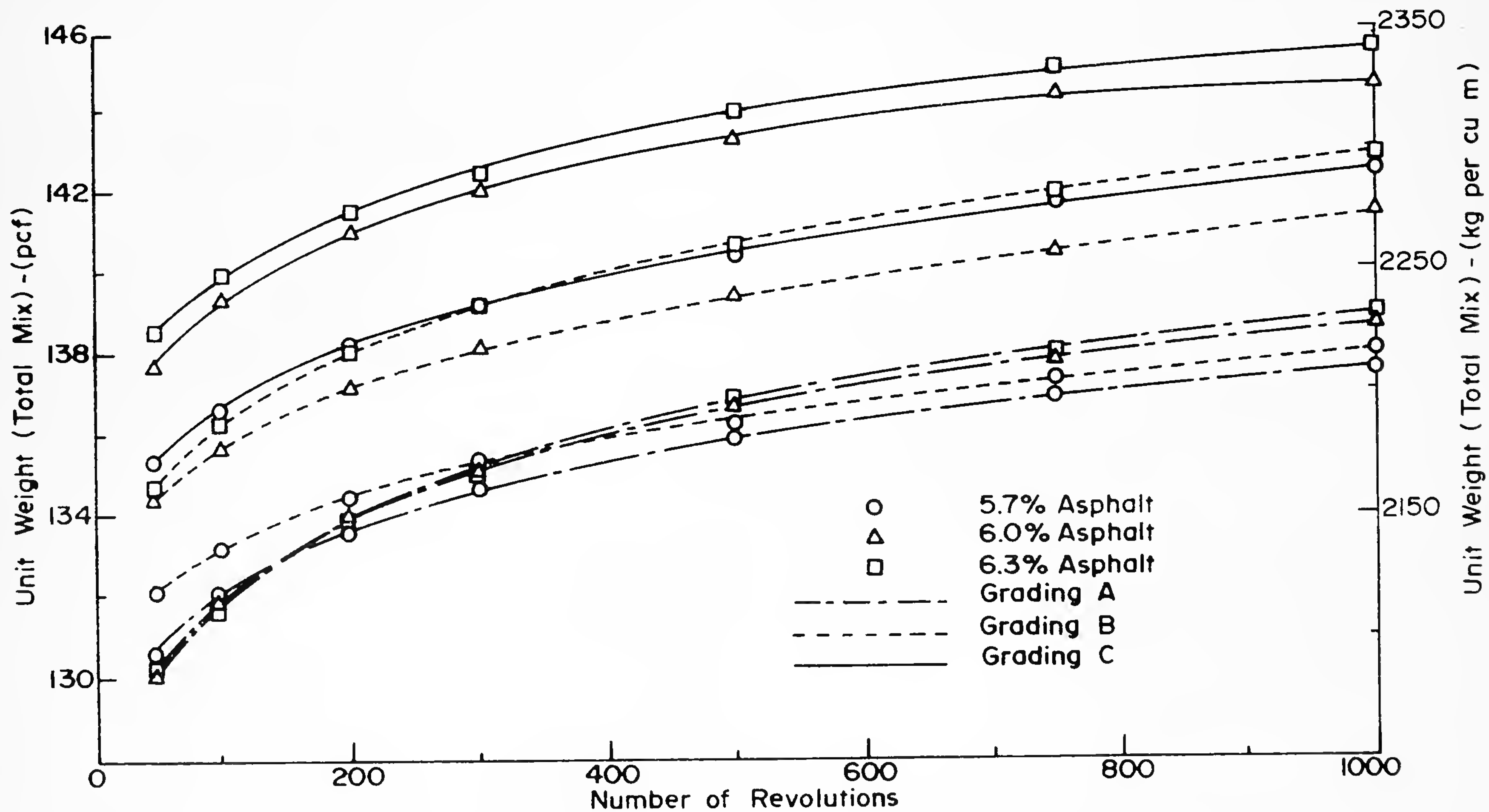


FIGURE A1 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - UNIT WEIGHT (TOTAL MIX).

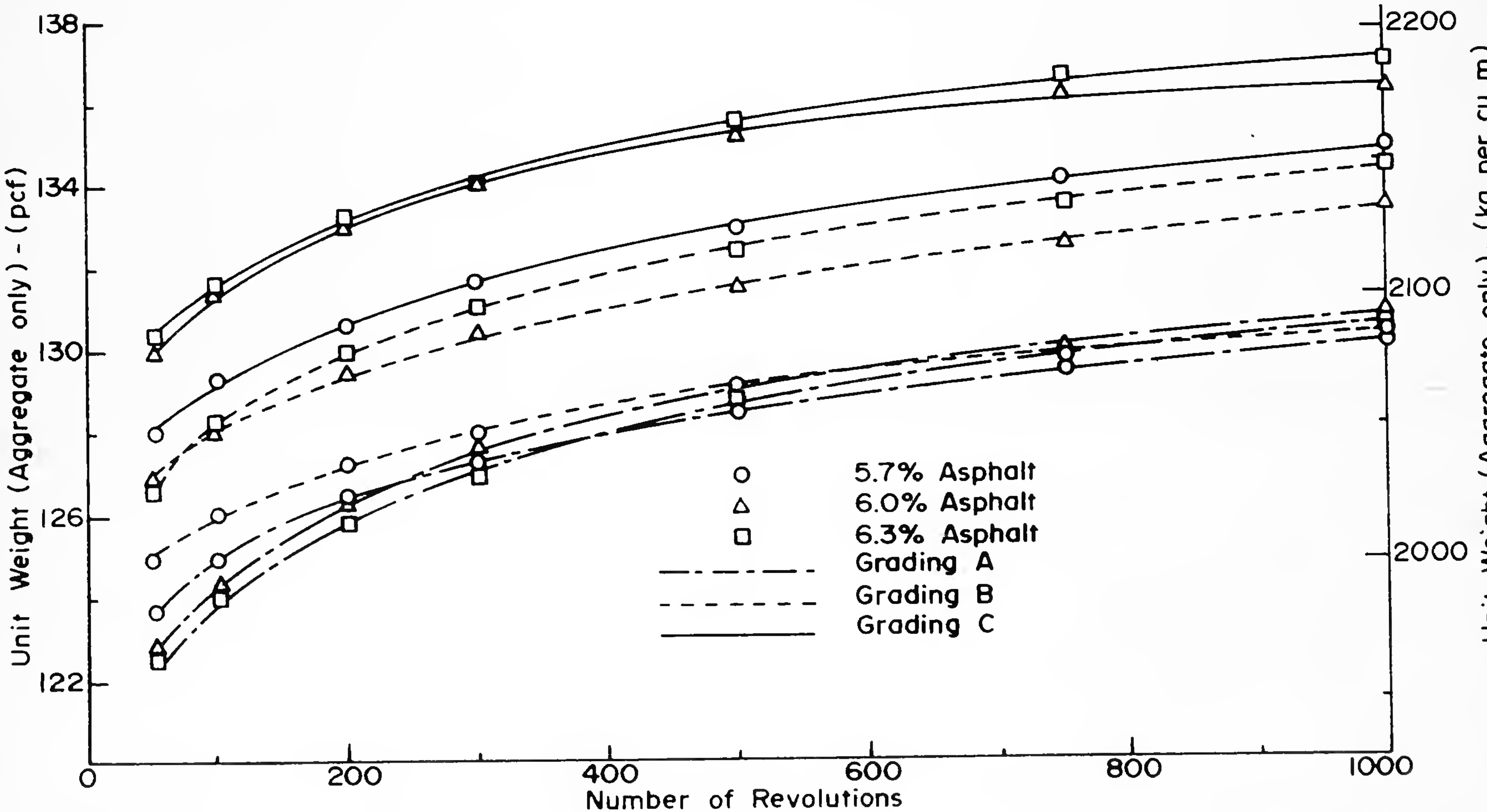


FIGURE A2 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - UNIT WEIGHT (AGGREGATE ONLY).

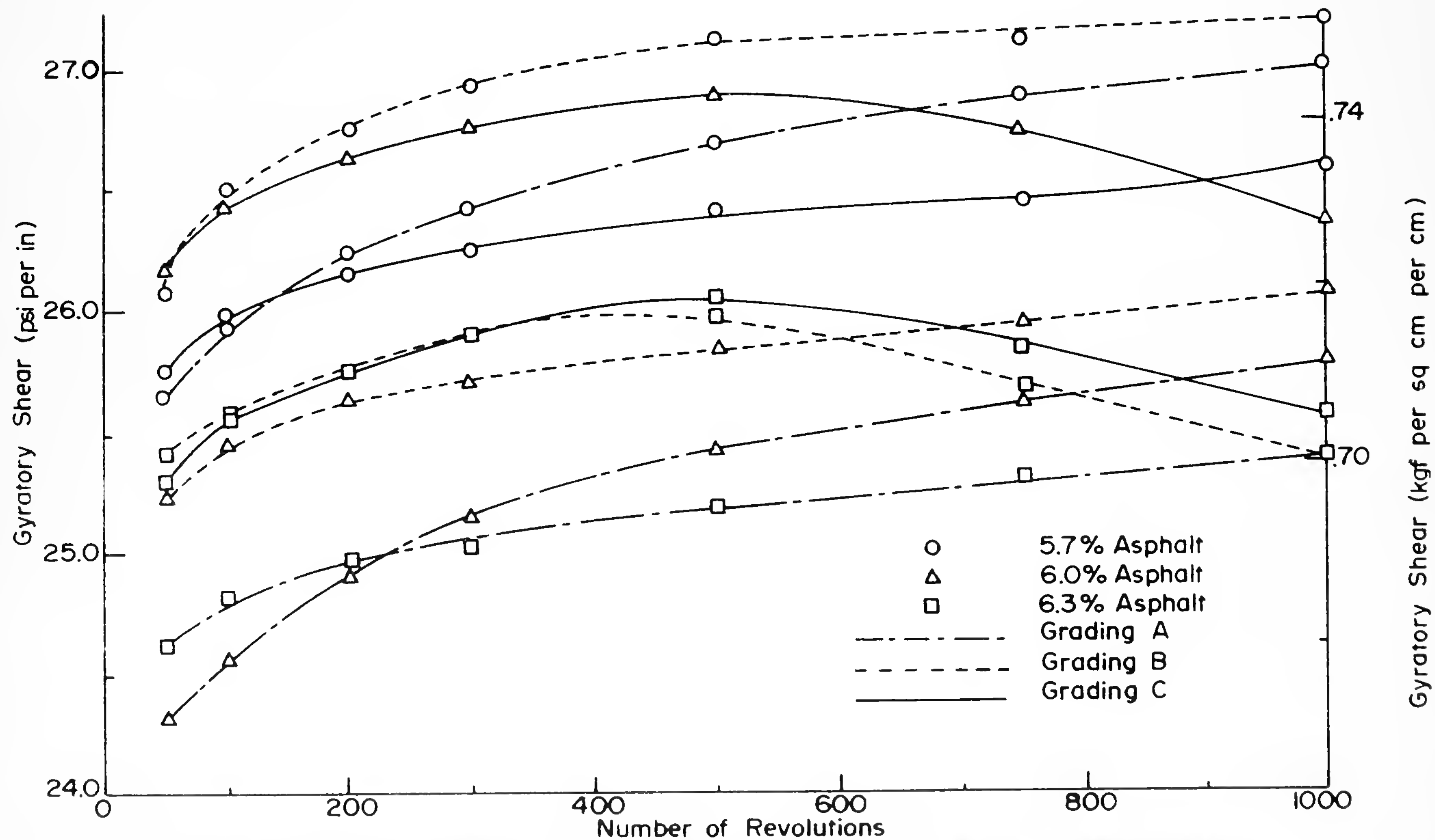


FIGURE A3 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - GYRATORY SHEAR .

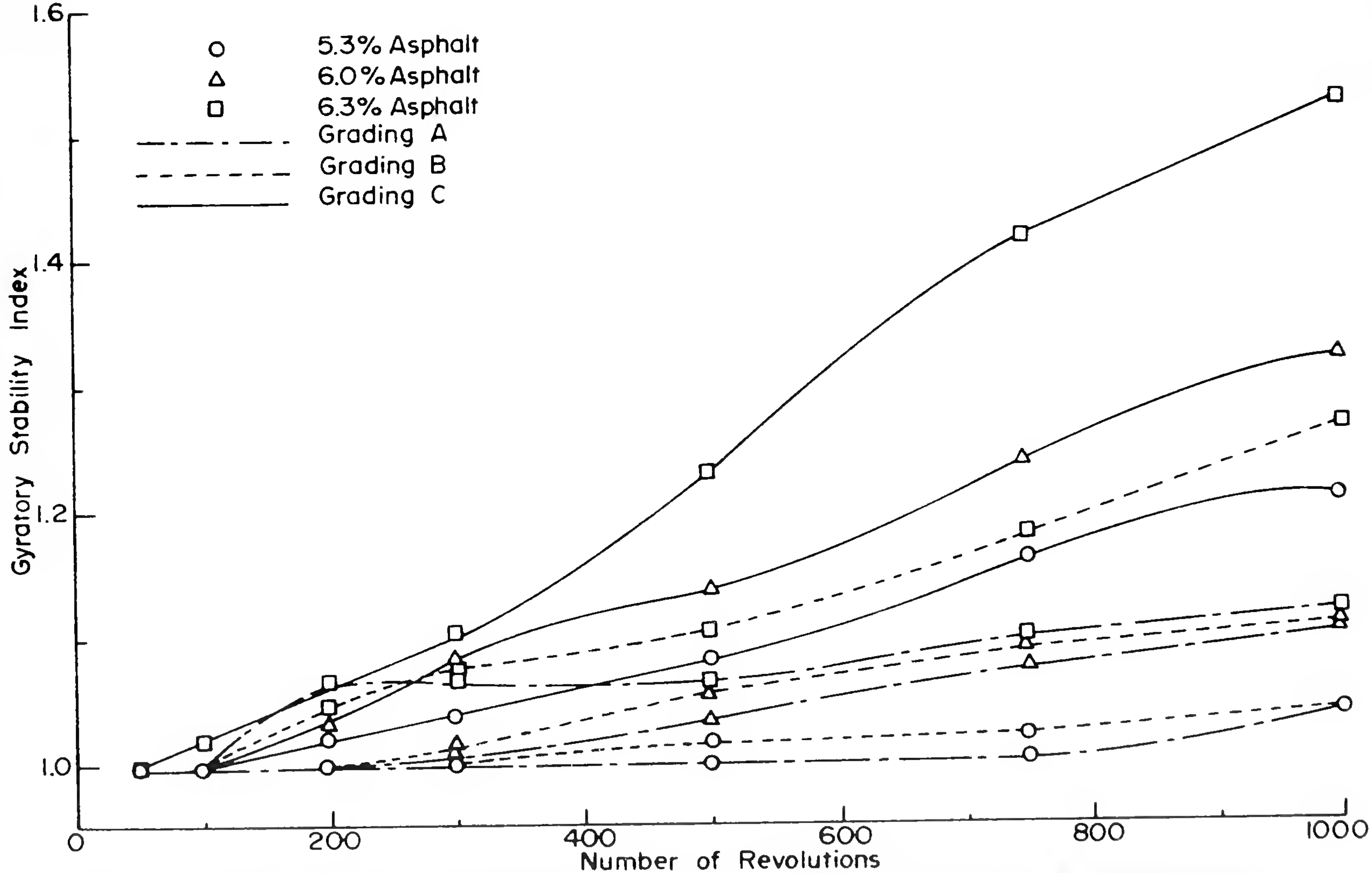


FIGURE A4 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - GYRATORY STABILITY INDEX (GSI_{50}^{x}).

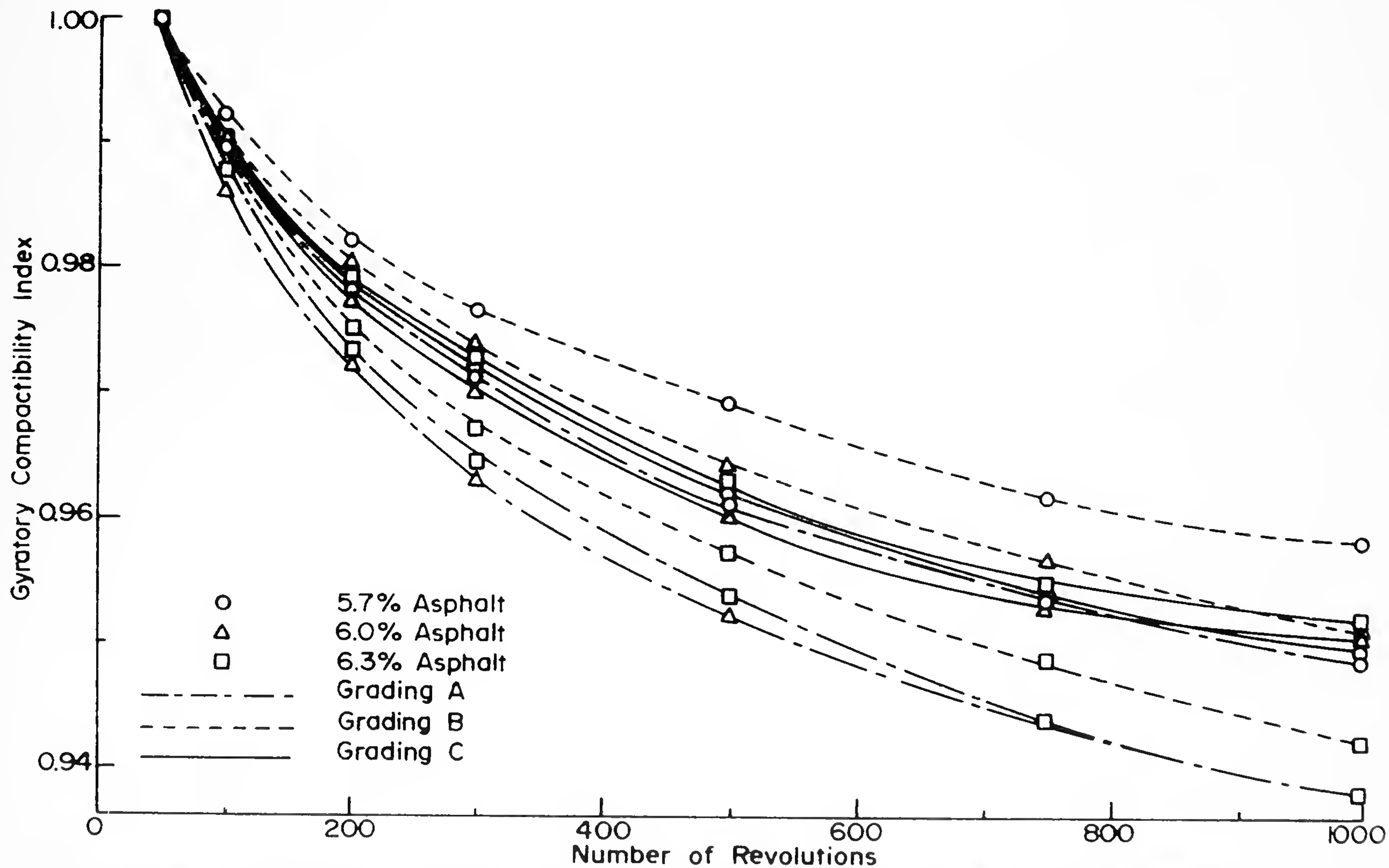


FIGURE A5 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - GYRATORY COMPACTIBILITY INDEX (GCI^{x}_{50}).

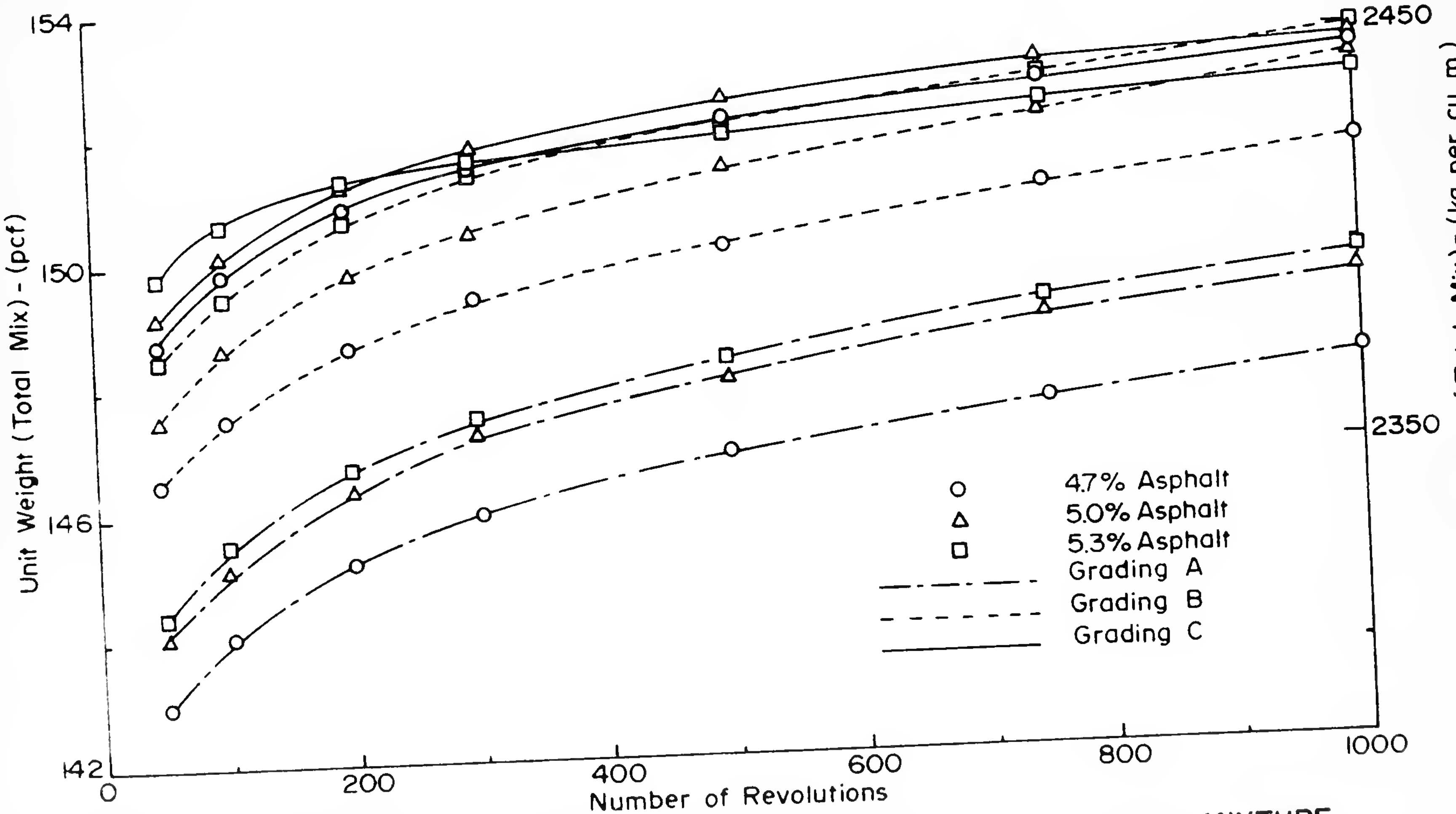


FIGURE A6- INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - UNIT WEIGHT (TOTAL MIX).

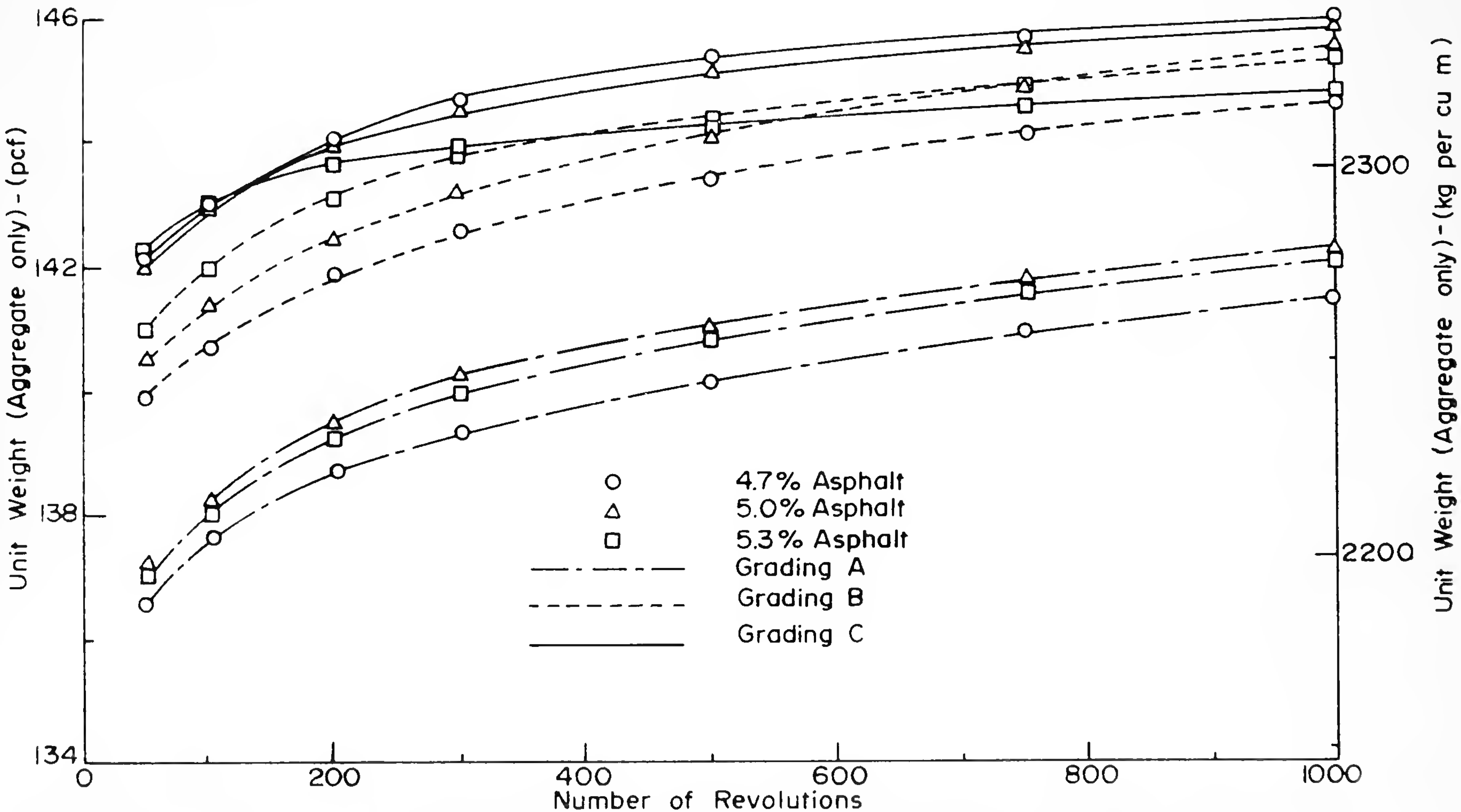


FIGURE A7- INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - UNIT WEIGHT (AGGREGATE ONLY).

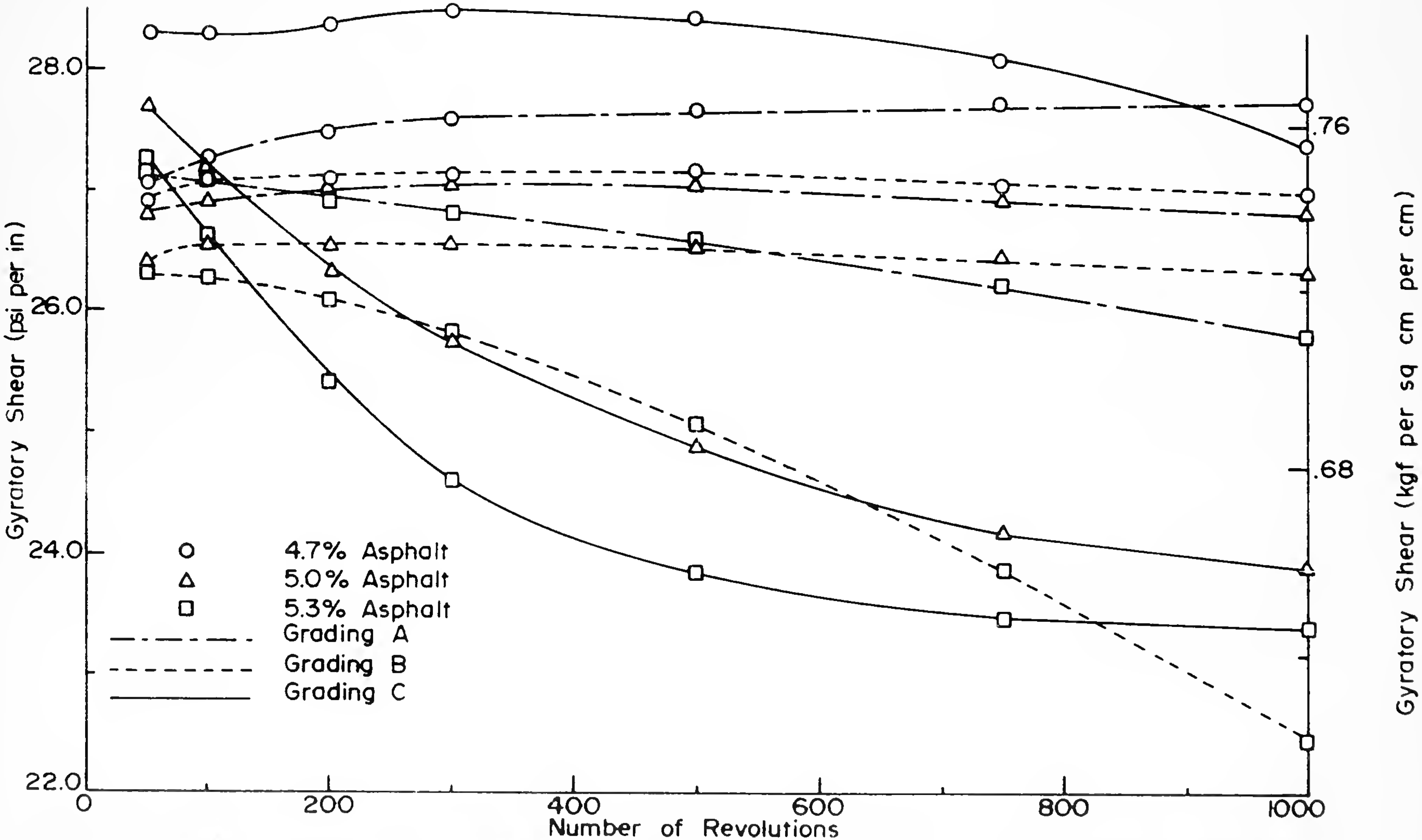


FIGURE A8 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - GYRATORY SHEAR.

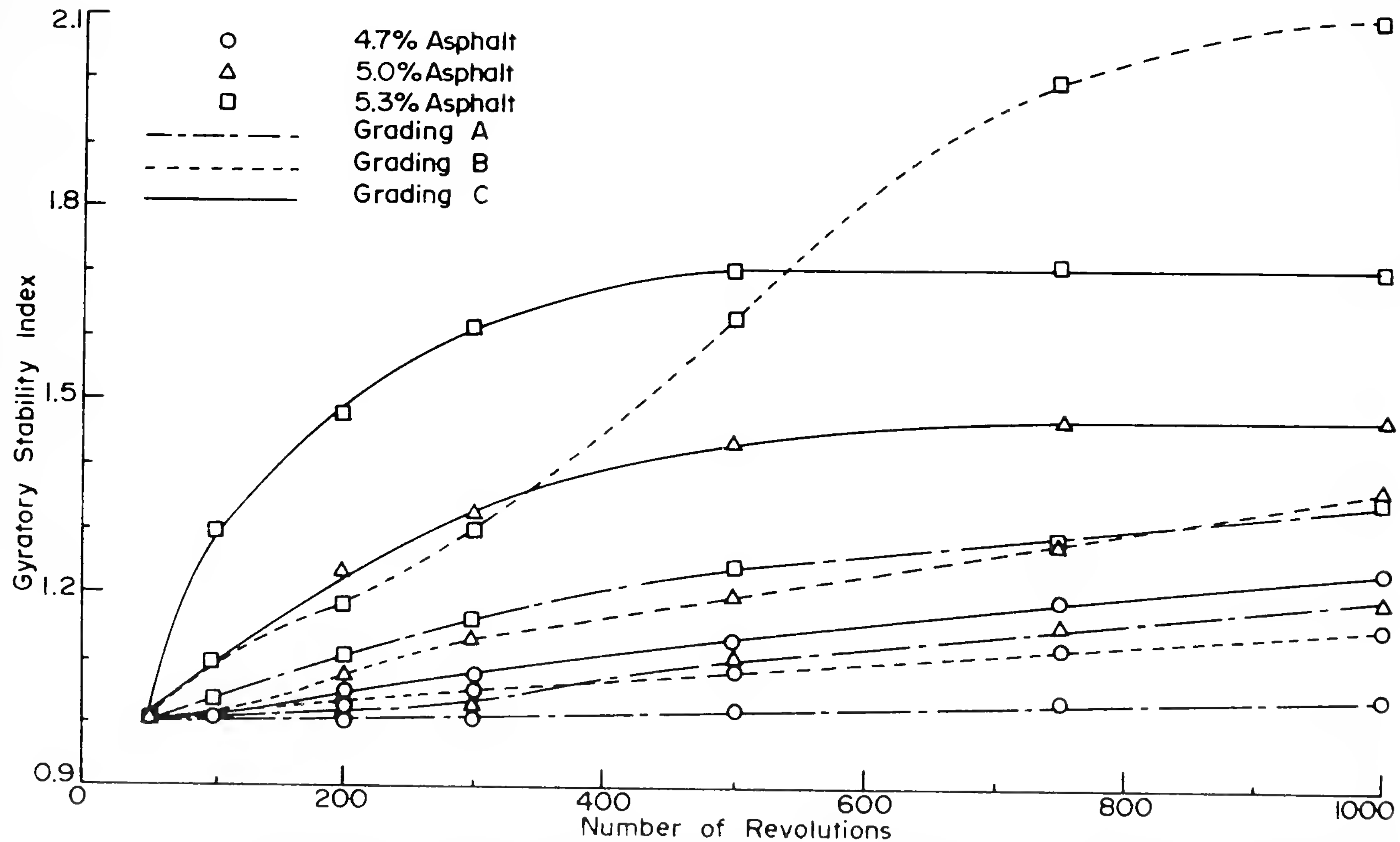


FIGURE A9 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - GYRATORY STABILITY INDEX (GSI^{x}_{50}).

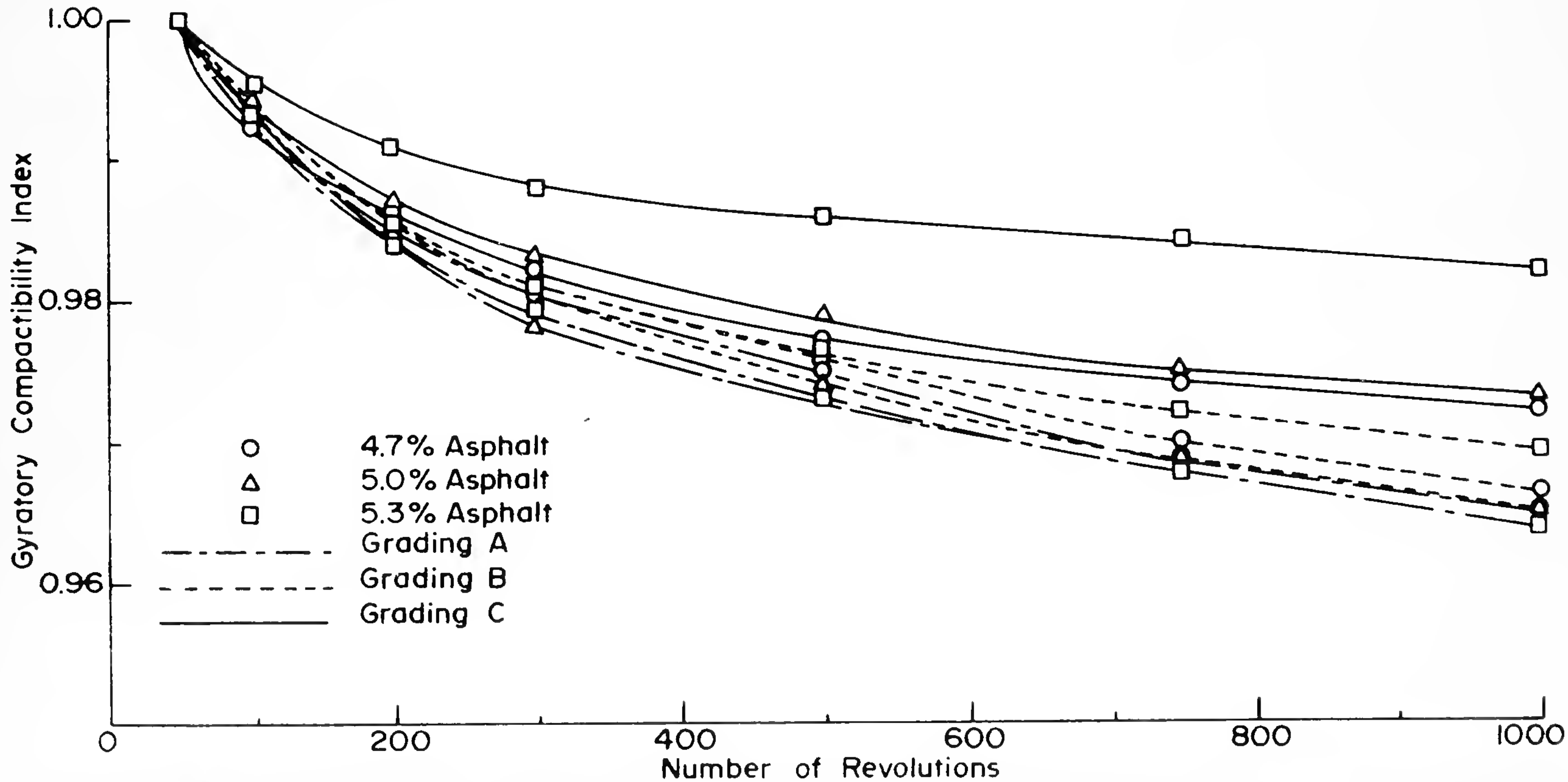


FIGURE A10 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - GYRATORY COMPACTIBILITY INDEX (GCI^{x}_{50}).

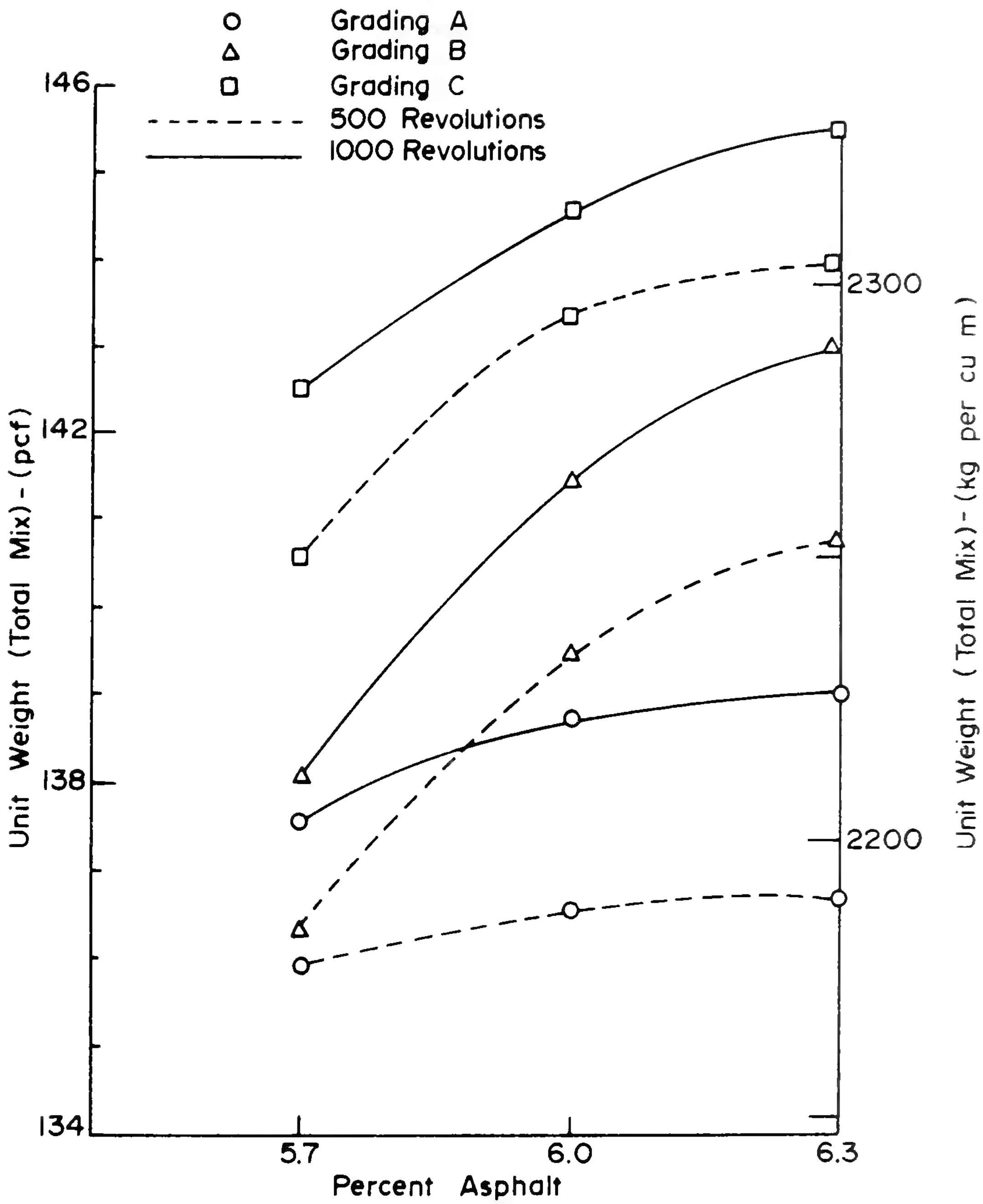


FIGURE A11 - UNIT WEIGHT (TOTAL MIX) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

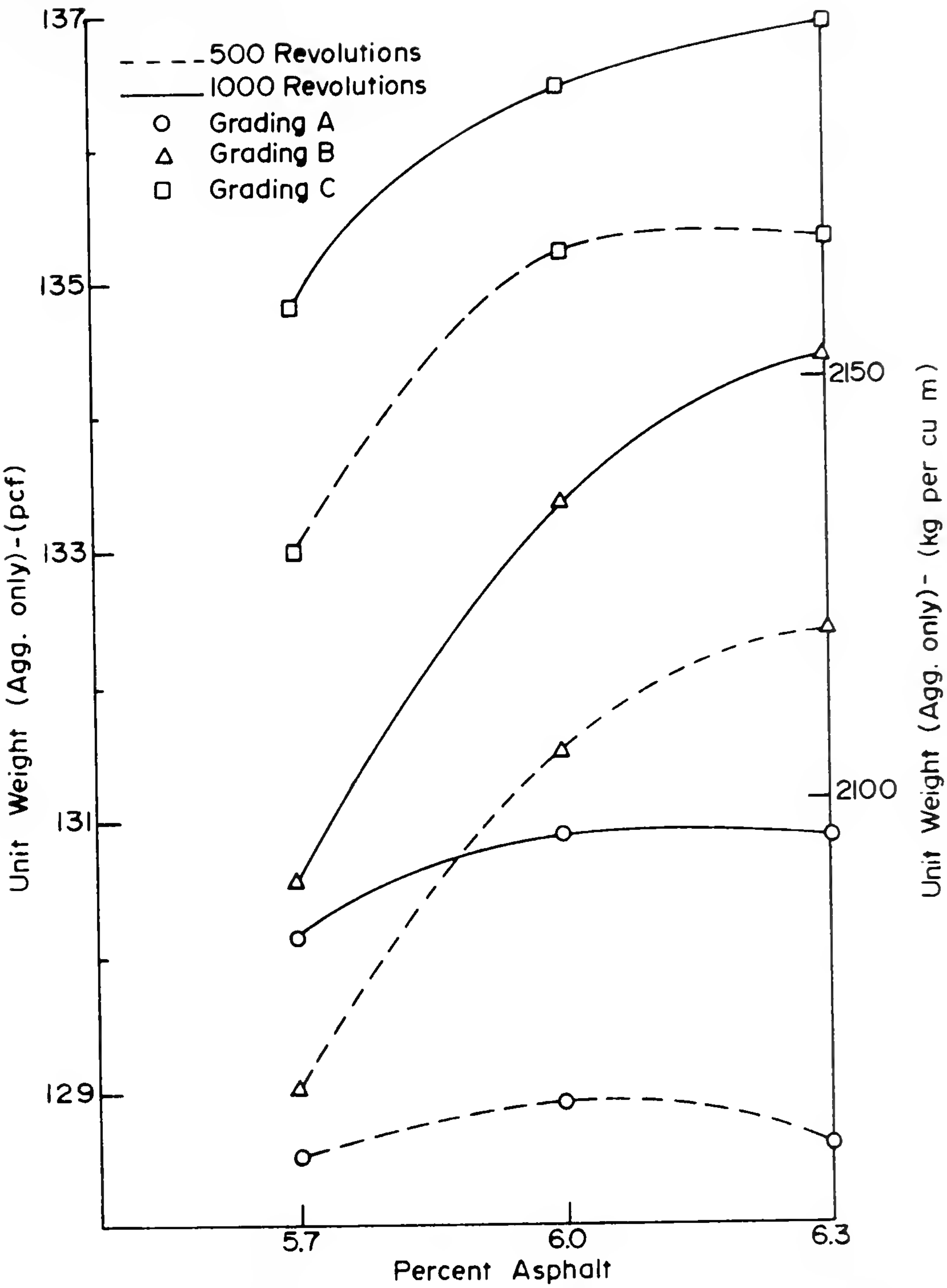


FIGURE A12 UNIT WEIGHT (AGGREGATE ONLY) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

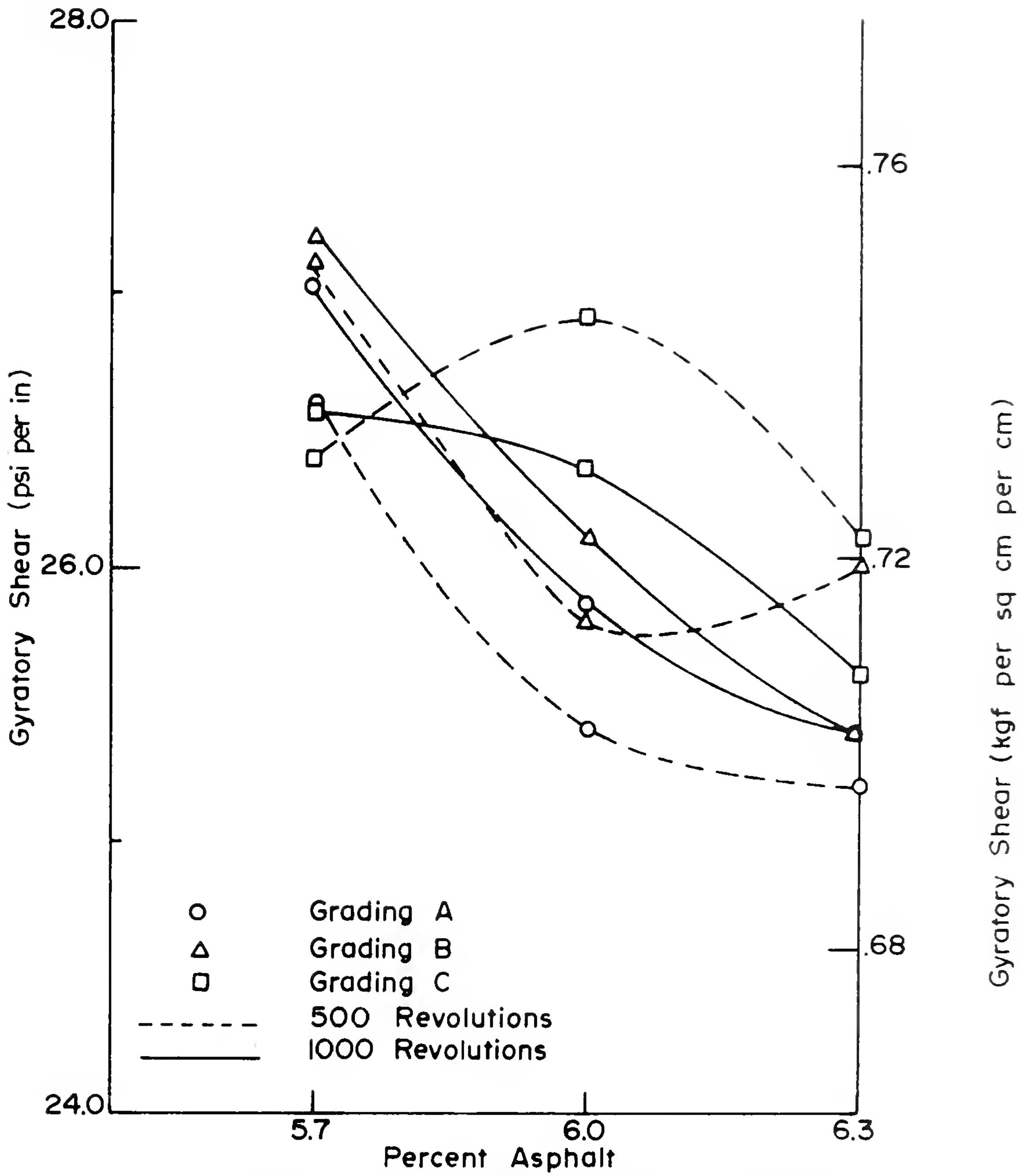


FIGURE A13 - GYRATORY SHEAR Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

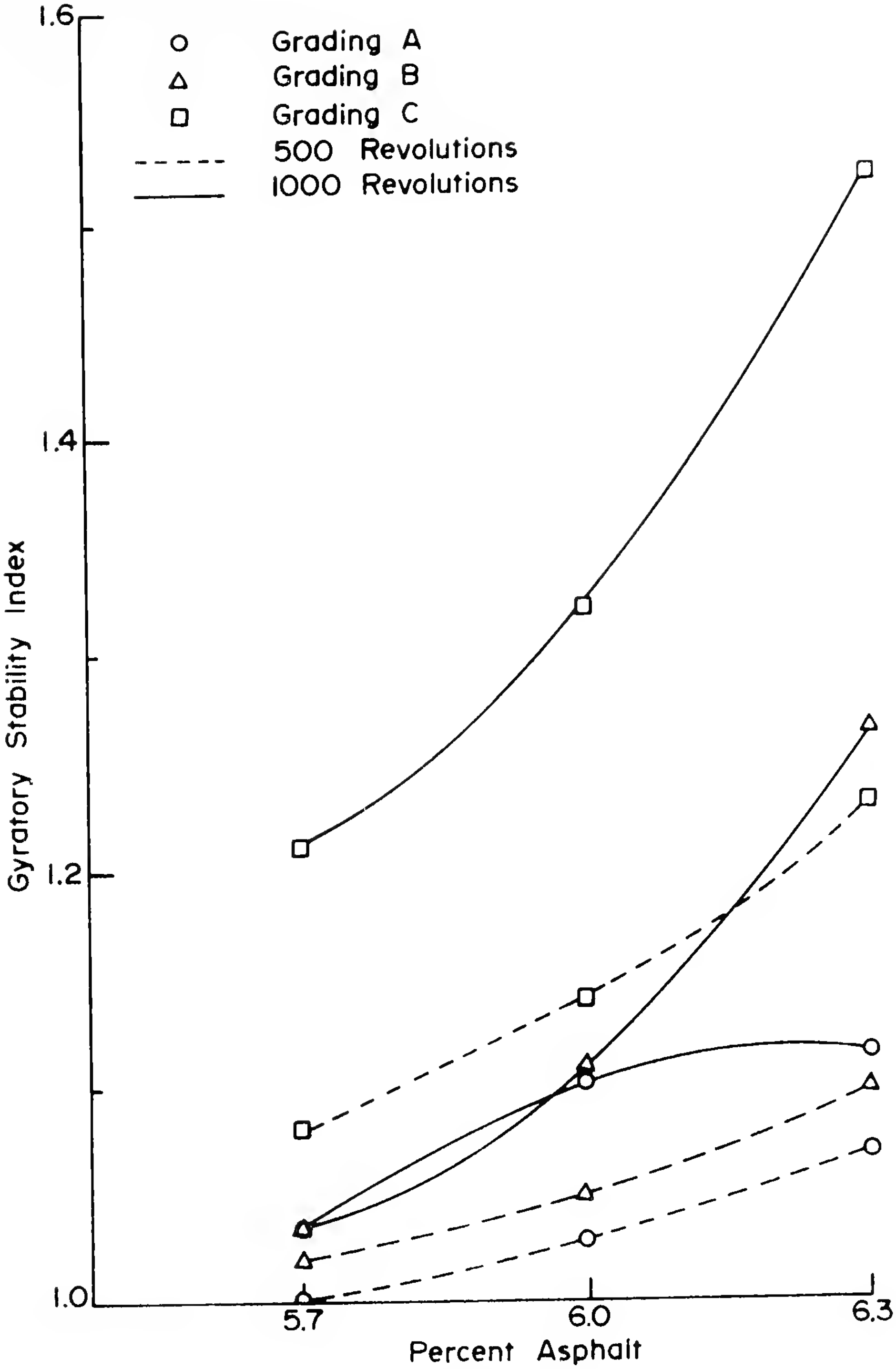


FIGURE A14-GYRATORY STABILITY INDEX (GSI^{x}_{50}) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

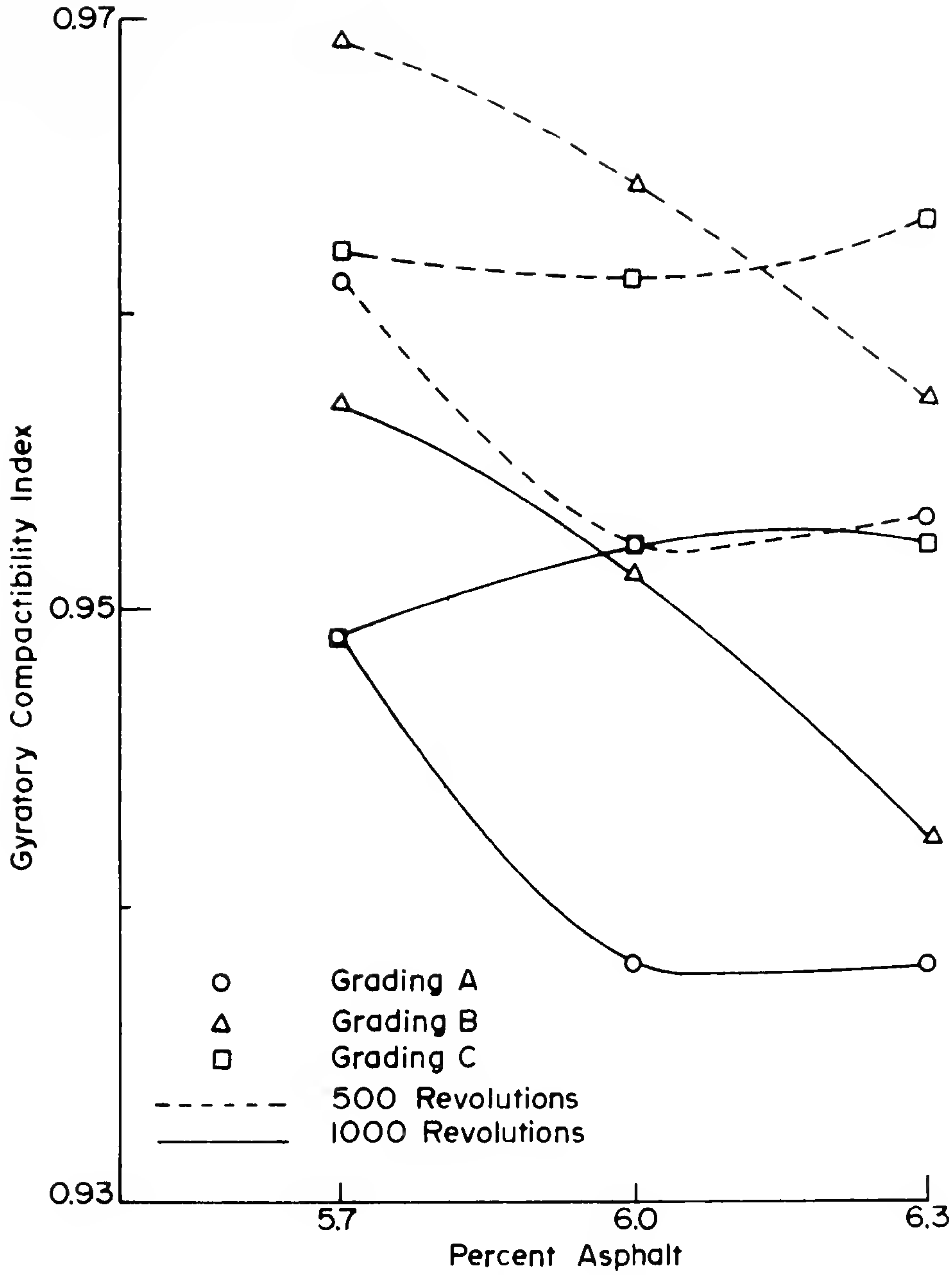


FIGURE A15 GYRATORY COMPACTIBILITY INDEX (GCI^{x}_{50}) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

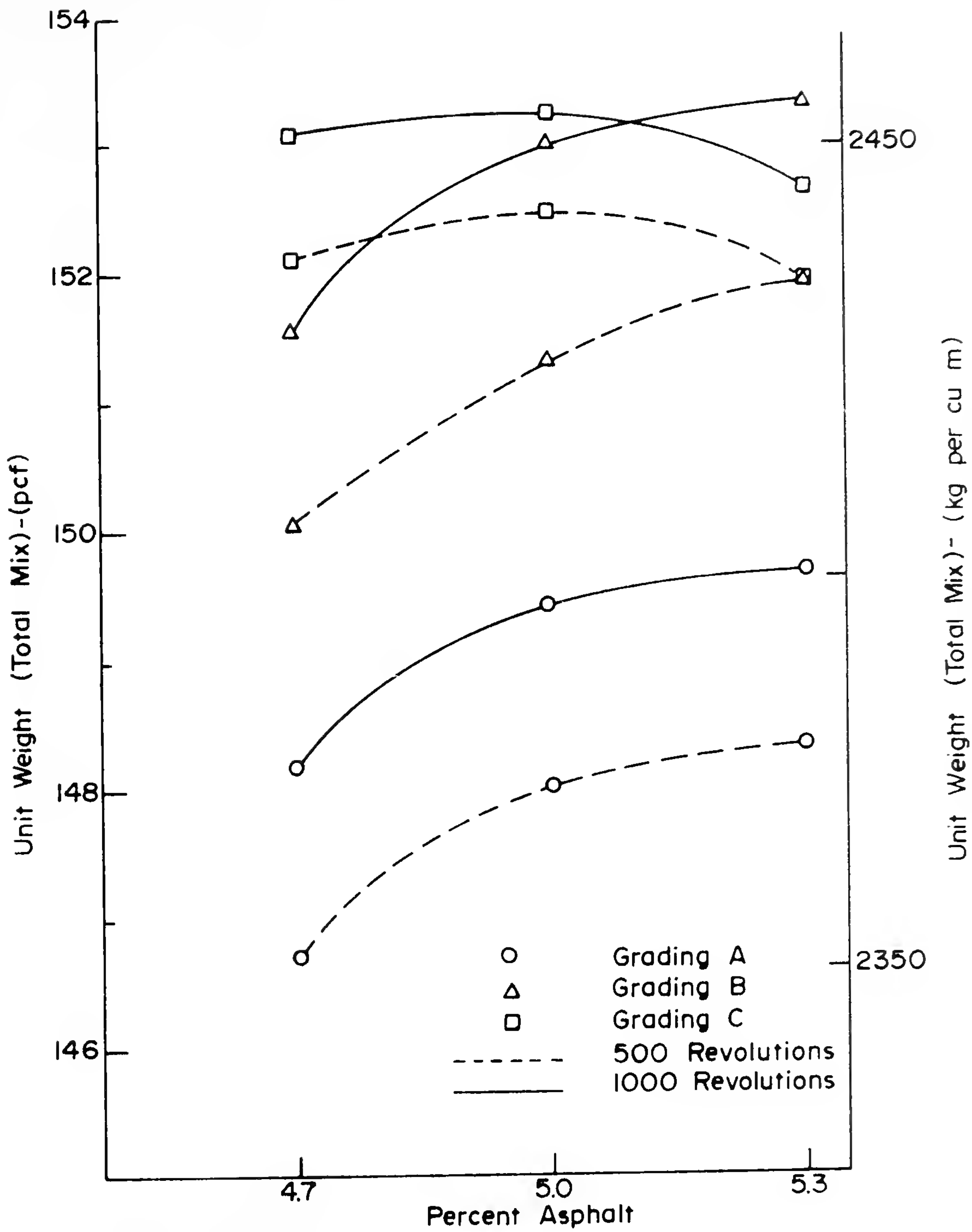


FIGURE A16 UNIT WEIGHT (TOTAL MIX) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

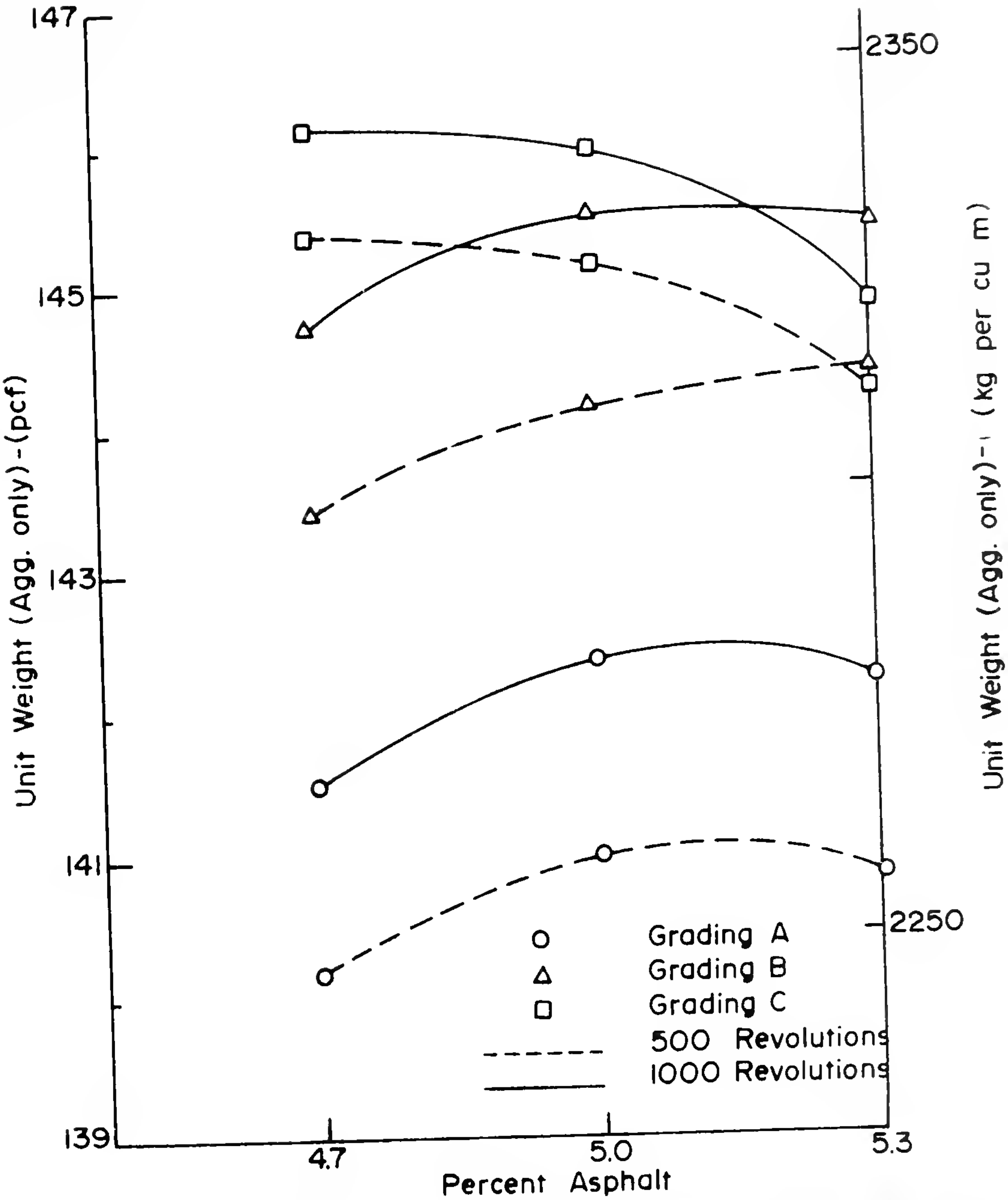


FIGURE A17 - UNIT WEIGHT (AGGREGATE ONLY) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

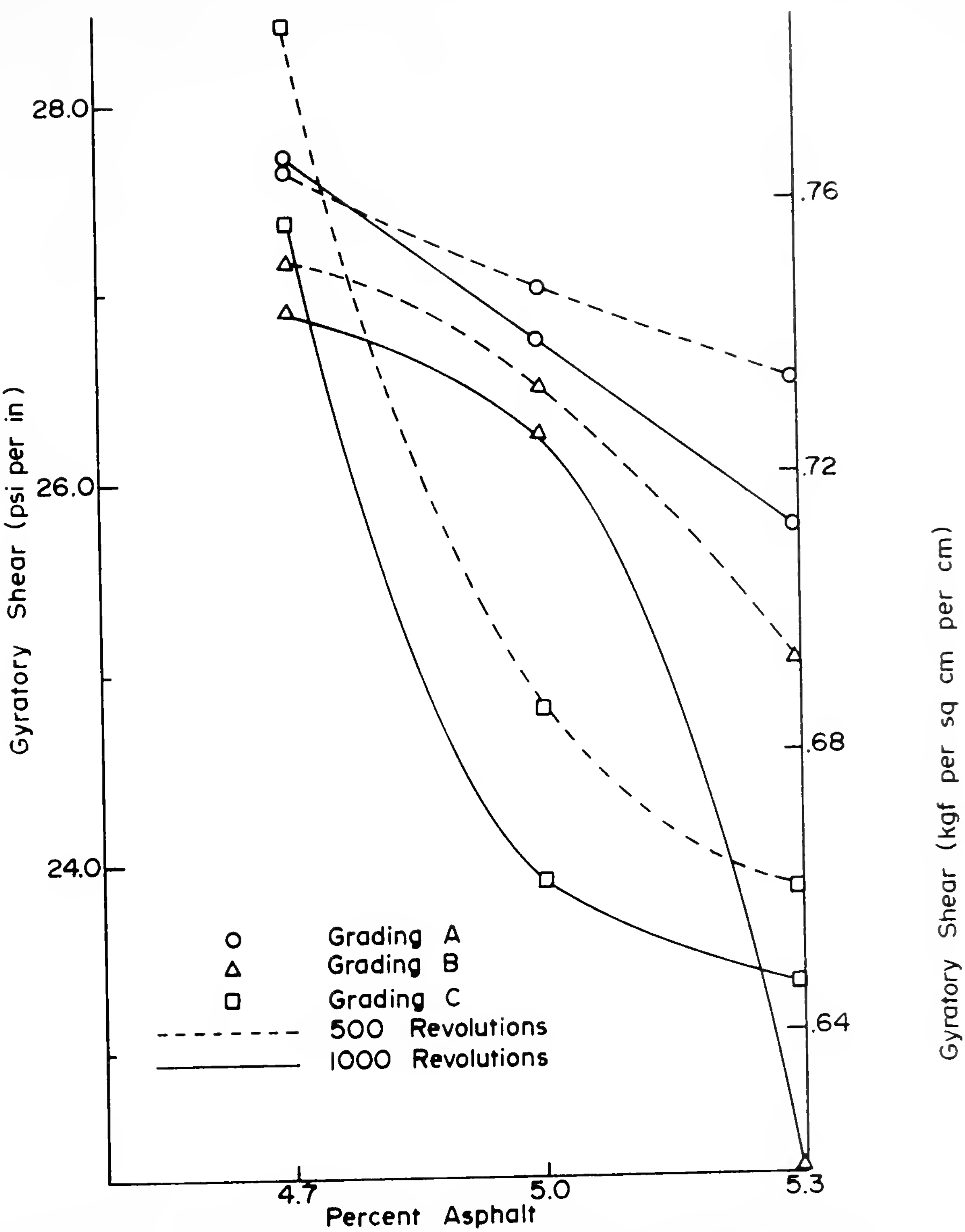


FIGURE A18 GYRATORY SHEAR Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

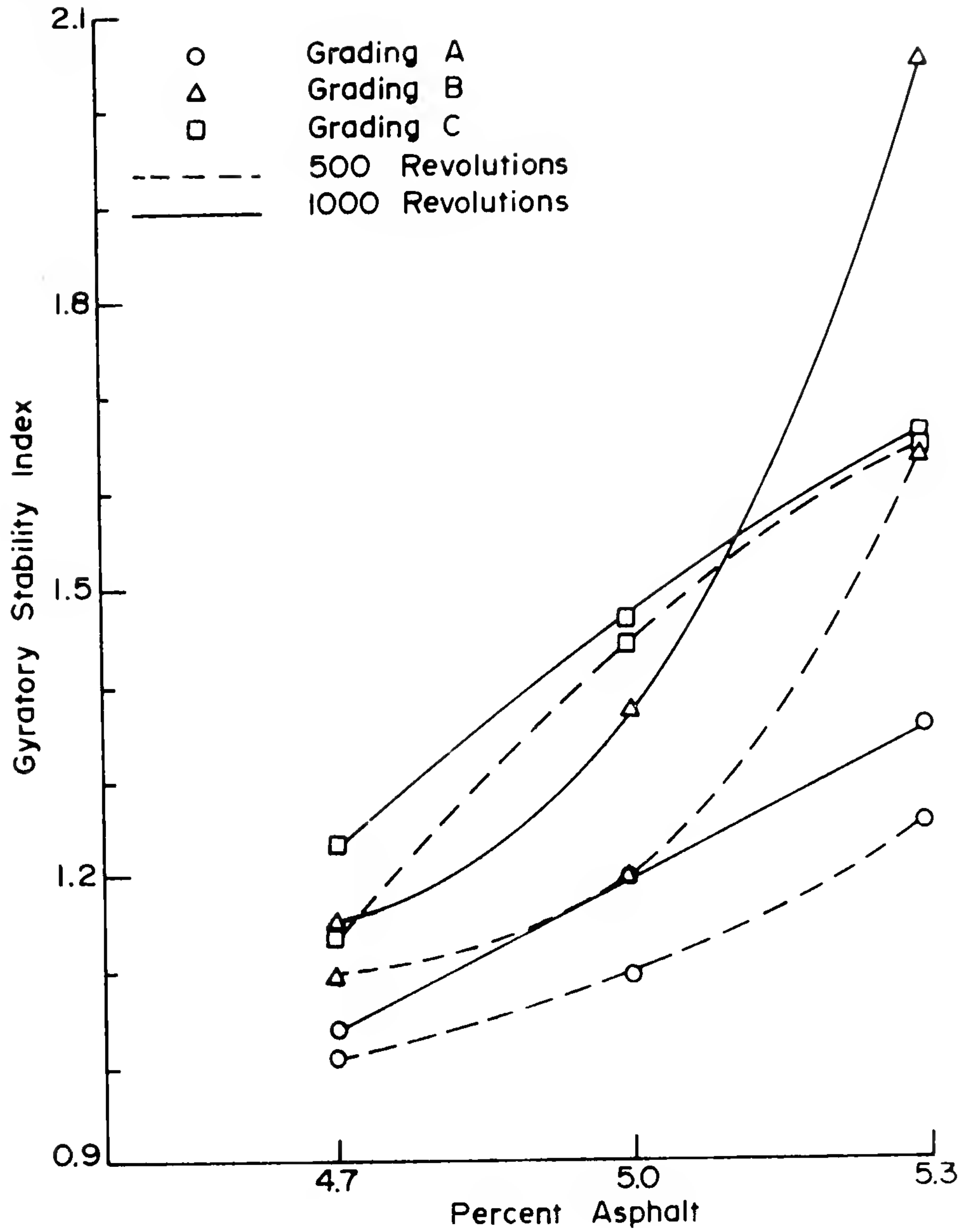


FIGURE A19-GYRATORY STABILITY INDEX (GSI^x_{50}) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

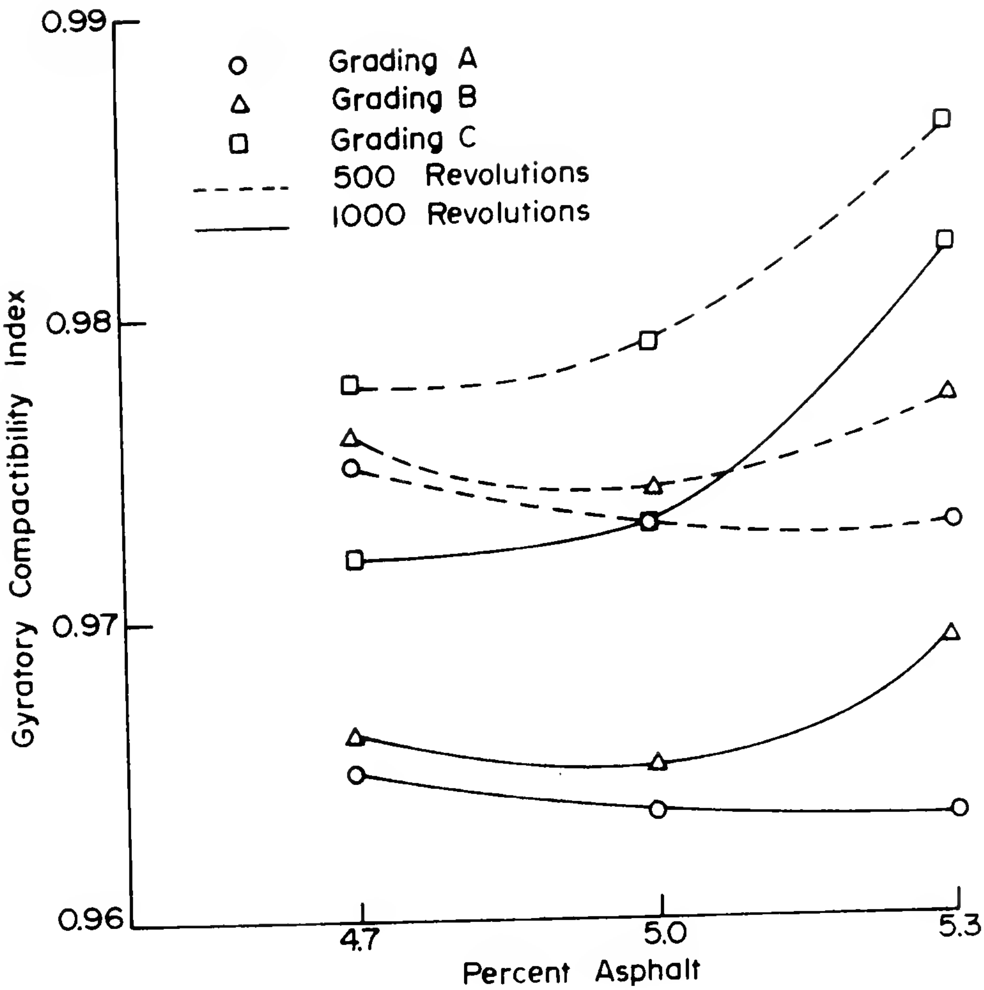


FIGURE A20 GYRATORY COMPACTIBILITY INDEX (GCI^{x}_{50}) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

COVER DESIGN BY ALDO GIORGINI